

THE GENEVA SERIES ON THE PEACEFUL USES OF ATOMIC ENERGY

DR. J. G. BECKERLEY, GENERAL EDITOR



ALLAMA IQBAL LIBRARY



31496







# EXPLORATION FOR NUCLEAR RAW MATERIALS



# THE GENEVA SERIES ON THE PEACEFUL USES OF ATOMIC ENERGY

---

*Editor of the Series*

JAMES G. BECKERLEY

*Head, Engineering Physics Department,  
Schlumberger Well Surveying Corporation;  
Formerly Director of Classification  
United States Atomic Energy Commission*

---

NUCLEAR FUELS

*by David H. Gurinsky and G. J. Dienes*

EXPLORATION FOR NUCLEAR RAW MATERIALS

*by Robert D. Nininger*

NUCLEAR REACTORS FOR RESEARCH

*by Clifford K. Beck*

NUCLEAR POWER REACTORS

*by James K. Pickard*

SAFETY ASPECTS OF NUCLEAR REACTORS

*by C. Rogers McCullough*

NUCLEAR RADIATION IN FOOD AND AGRICULTURE

*by Ralph Singleton*



# EXPLORATION FOR NUCLEAR RAW MATERIALS

---

*Edited by*

ROBERT D. NININGER

*Assistant Director of Raw Materials for Exploration  
United States Atomic Energy Commission*



MACMILLAN AND CO. LIMITED  
ST. MARTIN'S STREET, LONDON



THIS BOOK IS COPYRIGHT IN ALL COUNTRIES  
WHICH ARE SIGNATORIES TO  
THE BERNE CONVENTION

**CHECKED**

*57.82*  
*catalog*  
*DM*



*539.76*  
*N 622 E*



PRINTED IN THE UNITED STATES OF AMERICA



“ . . . the United States pledges before you—and therefore before the world—its determination to help solve the fearful atomic dilemma—to devote its entire heart and mind to find the way by which the miraculous inventiveness of man shall not be dedicated to his death, but consecrated to his life.”

PRESIDENT DWIGHT D. EISENHOWER  
address before the General  
Assembly of the United Nations,  
December 8, 1953.







## FOREWORD

---

No matter how the Geneva Conference will be judged by historians of the future, there is one fact which will hardly be forgotten for some time to come: in ten days of August 1955 an unprecedented volume of technical information on atomic energy was put into the public record. Not all of the items of information were of equal value, to be sure, but relatively little was of a trivial nature.

Realizing that a verbatim record of this avalanche of data would be relatively indigestible to a large body of workers in the field, the Van Nostrand Company requested me to undertake the task of organizing and editing a series of books including that material of most urgent usefulness. Preprints of many of the conference papers were made available through the courtesy of the United Nations staff.

From a study of these papers it was concluded that about six volumes of nominal length would be required. Each would cover a specific subject and include the key papers, suitably edited to eliminate duplication and secondary material, and arranged in a logical manner.

Because of the great interest in finding the raw materials for the growing nuclear appetite, Robert D. Nininger, Assistant Director of Raw Materials for Exploration, United States Atomic Energy Commission, was asked to edit a volume on the geology of and the exploration for uranium and thorium. All atomic energy projects to date have had research reactors at the base of their technical efforts. Dr. Clifford Beck, Professor of Physics, North Carolina State College, whose foresight and determination put the first research reactor on a university campus, was asked to edit a volume on research reactors. At the center of the stage, particularly for the energy-hungry nations of the world, is the power reactor, a device of many and varied forms. James K. Pickard, now a consultant engineer on atomic energy developments, for many years previously one of the stalwarts of the AEC Reactor Development Division, consented to take on the task of a nuclear power reactors volume. Believing that one of the most difficult and urgent problems in the power reactor program is assessing the hazard and providing safety in reactor operation, it appeared urgent to include a volume devoted exclusively to reactor safety. One of the



pioneers in the field, Dr. C. R. McCullough of the Monsanto Chemical Company, has undertaken to edit a volume on the safety aspects of nuclear reactors. The heart of the power reactor is the nuclear fuel, the energy source and the focal point of intense metallurgical and solid state research efforts. Dr. David Gurinsky and Dr. G. J. Dienes of Brookhaven National Laboratory, who have made substantial contributions to these efforts, have edited a volume on nuclear fuels. In addition to the direct heat energy from fission, the ten per cent or so of reactor energy available as radiation is already exerting profound effect on civilization. One who has probed deeply into what might be termed the interaction of nuclear energy and agronomy, Dr. W. Ralph Singleton, Director of the Blandy Experimental Farm, University of Virginia, has edited the volume on nuclear radiation in food and agriculture.

These six volumes are not intended to cover all the technical areas of the Geneva Conference. Subjects such as radiobiology, nuclear physics, reactor physics, chemical processing—to name but a few—were not included (except where they touch on the subjects chosen) for a variety of reasons. A first consideration was that if all subjects were properly represented, the series would wind up as an ungainly large number of volumes. Reducing the number of volumes could only be done by limiting coverage either to a few papers on each subject or to a superficial digest of a large number of papers. It seemed a better choice to cover fewer topics more completely. A secondary consideration was an assessment of the state of the literature—where a subject was rather well represented in the public literature, it could be argued that the need for a corresponding volume was less urgent. Certainly, e.g., the literature of nuclear physics does not urgently require amplification. Moreover, although the nuclear physics papers published at Geneva were substantial, they did not disclose any striking new information. (In addition, many of the new nuclear data have been adequately disseminated by the United States Government handbooks.)

In any effort of this kind, arbitrary decisions are made in many places. Material is deleted, rearranged, and abbreviated and new material is added. It is hoped that these decisions have been wise and that the six volumes will be a fundamental reference work for the increasing number of scientists and engineers devoted to the peaceful uses of atomic energy.

J. G. BECKERLEY



## PREFACE

---

The principal significance of the International Conference on the Peaceful Uses of Atomic Energy in Geneva, with respect to the field of raw materials for nuclear fuels, was the presentation by 26 countries of up-to-date papers on the subject of uranium and thorium geology and exploration, indicating that at least that number of government-sponsored prospecting programs are under way. The 24 countries, collectively, submitted 125 papers, 98 on the natural occurrence of uranium and thorium and 27 on prospecting techniques. Of these, the U. S. Atomic Energy Commission and its contractors and the U. S. Geological Survey submitted a total of 85.

Until the Conference the only countries which had published significant information on the subject were Australia, Canada, France, the United Kingdom, and the United States. Of the newcomers to the field represented at the Conference, Brazil with five papers and Argentina with three were the leading contributors. The U.S.S.R. submitted only two papers, both on prospecting techniques.

Of particular interest was the entire collection of United States papers, particularly "Nuclear Fuel for the World Power Program," by Jesse C. Johnson, and "The Natural Occurrence of Uranium and Thorium," by Paul F. Kerr; the Brazilian paper on aerial radiometric surveying; the two Russian papers on aerial radiometric prospecting and radiohydrogeological prospecting; and the French paper on systematic surface radiometric prospecting.

It is interesting to note that prospecting theories and techniques developed in the various countries are very similar. Differences, where they exist, are in emphasis and are related to specific conditions in the country concerned.

The United States has a wide variety of geologic and terrain conditions, an excellent road network, and an enormous prospector population. Consequently, it has based its program on intensive coverage of the ground by individual prospectors.

The French have a small country, also very accessible, with rather uniform geology and topography in the mineralized areas, and very little private prospecting. They have been very successful in extremely detailed prospecting of



relatively small areas by government geologists looking primarily for one type of deposit.

The U.S.S.R. is a very large country, with only fair access and no private prospecting. It has a long history of extremely technical and scientific approaches to mineral exploration, particularly the use of geochemistry. The Russians, therefore, rely on a mass, government-directed attack on new areas, using all techniques available to them. They place great emphasis on geochemical prospecting of soils, waters, and vegetation, as well as on aerial prospecting and the development of geophysical methods. They use all available prospecting techniques in combination in exploring new areas and make an evaluation based on analysis of all the information collected by these various methods. Radiohydrogeological methods are normally used first in an area, followed by soil and vegetation sampling, aerial radiometric prospecting, and surface and subsurface geologic investigation.

The Brazilians have a very large, poorly explored country, with a limited number of geologists and engineers and private prospectors not yet educated in uranium and thorium exploration. They have relied to a large extent on the airplane for a preliminary evaluation of their resources.

The Canadians have a long history of private exploration and mine development by a class of professional prospectors and private and government mining engineers and geologists. Great areas of the country are extremely remote and difficult of access. Even the use of aircraft in prospecting is difficult. They have, therefore, relied largely on their traditional prospecting methods.

In spite of some difference of emphasis, the same general conclusions have been reached in all countries as to the methods that can be used, and most methods have been used to some extent. The United States program, however, has been undoubtedly the most versatile, and has had in addition the tremendous advantage over many countries of a large well-organized private prospecting program based on the incentive of profit.

The Conference papers represent in summary form the most up-to-date information on the subject of uranium and thorium geology and exploration yet available. A selection of thirty-three of the most significant papers has been used as the basis for this volume. Those parts of these papers which are not significant or relevant or which present information duplicated in other papers have been deleted, and the whole has been assembled in logical order. Papers that present several aspects of the subject have been divided into parts and the parts are placed in proper sequence in the volume.

*Exploration for Nuclear Raw Materials* comprises an Introduction, "Uranium Resources for the World Power Program," from the paper by Jesse C. Johnson, Director of Raw Materials, U. S. Atomic Energy Commission; and two parts, The Geology of Uranium and Thorium, and Techniques of Prospecting for Uranium and Thorium.



Part I comprises an introduction consisting of a condensation of the summary paper on the natural occurrence of uranium and thorium prepared on behalf of the United Nations by Professor Paul F. Kerr, Columbia University, and four additional chapters comprising five United States papers which most adequately represent the important information dealing with the theory of uranium occurrence, including the brief summary of uranium and thorium geology presented to the Conference by Dr. Lincoln R. Page, Assistant Chief Geologist, U. S. Geological Survey, based on all the United States papers submitted.

Part II is divided into thirteen chapters comprising parts of twenty-five of the twenty-seven papers on prospecting techniques, arranged in order of the specific aspects of the subject covered. Papers from the United States, the United Kingdom, Canada, Brazil, the U.S.S.R., and France are represented.

In preparing this volume, only limited use has been made of explanatory notes. For additional or more detailed information than is provided in the Conference Papers, there is available the large volume of publications of the U. S. Atomic Energy Commission and the U. S. Geological Survey, available through the Technical Information Service, Department of Commerce, the U. S. Geological Survey, and the Superintendent of Documents, Government Printing Office, Washington, D. C.

Almost every chapter includes a list of selected references. In addition, the reader is referred to the lists of Conference Papers at the end of the book for additional specific information on occurrences and deposits of uranium and thorium in the various countries, and to *Minerals for Atomic Energy*, by Robert D. Nininger (2d edition, D. Van Nostrand Company, Inc., Princeton, N. J., 1956) for a summary of such information and for general background information on the entire subject of uranium and thorium geology and exploration.

R. D. N.

Washington, D. C.

April 1956





# CONTENTS

---

CHAPTER	PAGE
FOREWORD	vii
PREFACE	ix
INTRODUCTION—URANIUM RESOURCES FOR THE WORLD POWER PROGRAM	1
PART I: THE GEOLOGY OF URANIUM AND THORIUM	
1. THE NATURAL OCCURRENCE OF URANIUM AND THORIUM	7
Original Sources of Uranium and Thorium	7
Mechanisms of Transport and Deposition	19
Types of Uranium and Thorium Deposits	23
Older Uranium Mineralization (Veins)	26
Younger Uranium Mineralization (Veins)	28
Uranium in Ancient Sediments	30
Thorium by Direct Crystallization	31
Uranium Accumulations in Sedimentary Strata	32
Uranium in Bituminous Strata	38
Uranium in Phosphate Rock	43
Thorium-bearing Detrital Deposits	44
Interpretations of Origin	46
2. THE NATURAL OCCURRENCE OF URANIUM IN THE UNITED STATES	52
3. THE GENESIS OF URANIUM DEPOSITS	55
Uraniferous Igneous Rocks, Pegmatites, and Migmatites	56
Uranium in Hydrothermal Vein and Replacement Deposits	57
Uranium Deposits in Sandstone	59
Uraniferous Coal and Associated Carbonaceous Shale	63
Uraniferous Black Shale	66
Uraniferous Marine Phosphorites	68
4. URANIUM PROVINCES	71
Processes That Concentrate Uranium	72
Influence of Orogeny on Uranium Concentration	77
Applications of the Province Concept to Prospecting	79



CHAPTER	PAGE
5. INFLUENCE OF REGIONAL STRUCTURE ON URANIUM OCCURRENCE IN THE WESTERN UNITED STATES	83
The Cordilleran Foreland	83
Influence of Structure on Lithology	85
Tectonic Analysis of the Region	87
Localization of Uranium Districts by Tectonic Elements	88
Influence of Regional Structure in the Colorado Plateau	90
PART II: TECHNIQUES OF PROSPECTING FOR URANIUM AND THORIUM	
6. INTRODUCTION: SURVEY OF PROSPECTING TECHNIQUES	101
Geologic Techniques	102
Geochemical Techniques	104
Geophysical Techniques	104
Engineering Techniques	105
General Experience in Canada	105
7. GEOLOGIC PROSPECTING	108
Introduction	108
Rock Alteration Criteria	115
Heavy Minerals	121
Exploration of Shinarump Channels, Colorado Plateau	126
8. A SYSTEMATIC METHOD OF EXPLORATION FOR AND EVALUATION OF URANIUM DEPOSITS IN FRANCE	131
The Method of Exploration	134
9. RADIOMETRIC PROSPECTING	139
Types of Instruments	139
Field Techniques	141
Calibration	141
Developments in Radiometric Instrument Circuits	143
10. SURFACE RADIOMETRIC TECHNIQUES	150
Types of Surface Surveys	150
Survey Techniques	152
11. AERIAL RADIOMETRIC TECHNIQUES	155
Basic Considerations	155
Types of Air-borne Surveys	156
Quantitative Interpretation: Air Scattering Effects	158
Aerial Radiometric Prospecting in the U.S.S.R.	164
Aerial Radiometric Prospecting in the United States	171



# CONTENTS

xv

CHAPTER	PAGE
Aerial Radiometric Prospecting in Brazil	177
Aerial Radiometric Prospecting in Canada	191
12. GEOPHYSICAL PROSPECTING	193
The Colorado Plateau Region	193
Surface Electrical Methods	194
Seismic Methods	197
Borehole Geophysical Methods	199
Other Geophysical Methods	200
Summary	201
13. GEOPHYSICAL-GEOCHEMICAL PROSPECTING	202
Field Survey Data	202
Discussion of Data	210
Reconnaissance Data	210
Experimental Data	212
14. GEOCHEMICAL PROSPECTING	213
Geochemical Anomalies	214
Analytical Methods for Geochemical Exploration	218
Determination of Elements	219
Application to Uranium Prospecting	222
15. BOTANICAL PROSPECTING	224
Prospecting by Tree Analysis	224
Prospecting by Indicator Plants	227
Results of Botanical Prospecting on the Colorado Plateau	230
16. HYDROGEOCHEMICAL PROSPECTING	232
Ground and Surface Water Sampling in the United States	234
Hydrogeochemical Prospecting in the U.S.S.R.	242
Use of Water Sampling in Location of Potential Uranium Source Beds	247
17. EXPLORATION DRILLING	256
Types of Drilling	257
Evaluation of Methods	258
Outlining Favorable Zones Using Widely Spaced Core Drilling	260
Drilling Patterns for (Shinarump) Paleochannels	265
18. SUBSURFACE RADIOMETRIC TECHNIQUES	268
Scintillation Drill-Hole Logging	269
LIST OF CONFERENCE PAPERS	277
SUBJECT INDEX	283
NAME INDEX	291







# *Introduction*

---

## URANIUM RESOURCES FOR THE WORLD POWER PROGRAM \*

---

The world's energy resources in the form of nuclear fuels far exceed those of all other types of fuel. There are adequate resources of uranium and thorium for a long-range expanding world power program.

Uranium will be the important nuclear fuel for the foreseeable future according to the present pattern of development and planning. For this reason the present review considers only present and potential uranium resources.

The Western nations which are cooperating in developing uranium production have achieved notable success. New sources of uranium have been found and brought into production. Former operations have been expanded and ore reserves extended. Information on uranium deposits and the nature of their occurrence has been greatly increased. Special instruments and techniques have been developed for use in exploring for radioactive minerals. New metallurgical processes for extracting uranium from ores have increased recoveries and reduced the cost of production. By-product uranium is being recovered commercially from very low-grade materials.

Today there are major uranium operations in the Belgian Congo, Canada, South Africa, and the United States. Australia, France, and Portugal also are producing uranium, with favorable prospects for substantially increased production. This uranium production program to a large extent has been carried out by private industry operating under a profit incentive system. However, government exploration and metallurgical research programs have played a major role in supporting private operations and in speeding developments.

Expenditures by the United States for exploration and development of exploration methods have amounted to approximately \$46,000,000, and for metallurgical research and pilot plant operations to over \$12,000,000. In 1948 the United States was considered by many to have relatively poor uranium prospects. Ore

\* Extracts from Geneva Conference Paper 470, "Nuclear Fuels for the World Power Program" by Jesse C. Johnson, Director, Division of Raw Materials, United States Atomic Energy Commission.



reserves are now increasing more rapidly than at any time since the program commenced.

One of the important conclusions to be drawn from the information gathered during the past seven years is that commercial uranium deposits of considerable size may be found in many areas and under a variety of geological conditions. It has long been known that in the earth's crust uranium is about as plentiful as lead or zinc, and is about one hundred times more plentiful than silver. However, it was rather generally assumed that concentrations in commercial deposits might be rare. This has not proved to be the case.

Because active prospecting and exploration have been undertaken in only a few countries and these countries are as yet only partially explored, we are not now in a position to estimate the uranium resources of the world. As the nuclear power program grows and the search for uranium is extended, more and more information will become available about the resources for the future. There is every reason to believe that these resources will be far larger than those we are considering today. However, the areas now producing or under active development assure an adequate supply of uranium for a long-range power program.

On the basis of present developments and geological evidence, resources of the producing nations of the West are estimated to be between one and two million tons of uranium. This is uranium that can be produced at moderate cost, at an average of about \$10 a pound for  $U_3O_8$  in a high-grade concentrate.

In the more distant future, the fuel requirements for the atomic age may come from the vast low-grade uraniferous phosphate and shale deposits. Reserves of commercial phosphate rock in the United States alone are estimated at five billion tons and the uranium content at six hundred thousand tons. These reserves would be greatly increased by including low-grade phosphatic rock not presently considered commercial. The United States also has an estimated eighty-five billion tons of marine shale averaging slightly more than one-tenth of a pound of uranium per ton. This represents a reserve of five to six million tons of uranium.

Known deposits of uraniferous phosphate rock and shale in other parts of the world equal or exceed those of the United States in grade and tonnage. For example, the phosphate deposits of Morocco, estimated at twenty billion tons, are uranium-bearing. The Scandinavian Peninsula and other Baltic territories contain very large deposits of uraniferous shale. Uranium-bearing coal and lignite also have been found in a number of countries.

The cost of extracting uranium as the primary product from phosphate and shales may be between \$30 and \$50 per pound. If valuable by-products can be recovered, the cost may be reduced. Furthermore, uranium can be recovered at moderate cost as a by-product from some commercial phosphate fertilizer and chemical operations. This already is being done. Approximately ten mil-



lion tons of commercial phosphate rock are mined annually in the United States. If all of this rock were processed to phosphoric acid, in excess of one thousand tons of by-product uranium oxide might be recovered annually.

Between the commercial uranium deposits of today and the high-cost uranium resources of the more distant future, there are deposits that could supply uranium at a cost of between \$10 and \$30 a pound. The resources in this economic class are not well known, but they must be large—perhaps several million tons of uranium. These resources will include deposits of types now being mined, but which are outside the economic limits prevailing today. We already know of some such large reserves, but most of the information on resources in this category must come from future exploration. Experience gained from the present uranium program has demonstrated that higher prices will bring in new sources of production and increase available reserves.

This general review of resources indicates that uranium can no longer be considered a rare metal. There are extensive deposits throughout the world and there are processes for extracting the uranium economically. The uranium production already developed is sufficient for a major nuclear power program of world-wide extent. Additional production can be obtained when needed. When the vast low-grade resources are required, more efficient use of nuclear fuel, e.g., through improved conversion or breeding in nuclear reactors, may offset the higher uranium cost.





# *Part One*

---

## THE GEOLOGY OF URANIUM AND THORIUM





# *Chapter 1*

---

## THE NATURAL OCCURRENCE OF URANIUM AND THORIUM \*

---

---

Uranium and thorium are found in a variety of rocks and in widely different formations. However, three broad source types stand out as the most productive: (1) belts of ancient pre-Cambrian rocks, (2) widespread areas of permeable sediments, and (3) accumulations of detrital sands. The great belts of ancient (pre-Cambrian) crystalline rocks exposed on each continent are distinctive either as existing or potential sources of uranium and thorium (Fig. 1.1). Uranium deposits in such rocks include the occurrences of Czechoslovakia, the Canadian Shield, the Belgian Congo, South Africa, and Australia. Thorium deposits would include the peninsula of India, the hinterland behind the coastal areas of Brazil, and the piedmont of the Carolinas in the United States.

Major occurrences of uranium are found in permeable sediments. In this form of occurrence the area of greatest productivity reported would be the great region of plateau sediments and intermountain basins of the western United States. As indicated in the older literature, a similar district may exist in the Ferghana area, U.S.S.R. Major occurrences of thorium are also found in detrital sands of comparatively recent geological age. Such deposits are well-known along the coastal belt of India and along the northeast shore of Brazil, as well as in the Carolinas and in Idaho in the United States.

### ORIGINAL SOURCES OF URANIUM AND THORIUM

**Traces in igneous rocks.** Quantitative data on the elements found in igneous rocks of the earth's crust are uncertain, and estimates of amounts vary.

\* Extracts from Geneva Conference Paper 1114, "The Natural Occurrence of Uranium and Thorium" by Paul F. Kerr, Department of Geology, Columbia University, New York. This paper was prepared for the United Nations.

Selected references indicated by author surname and date are listed alphabetically by author at the end of the chapter. Conference paper references are denoted by "GC" followed by a number; thus "(GC 761)" refers to Geneva Conference Paper 761. A list of the



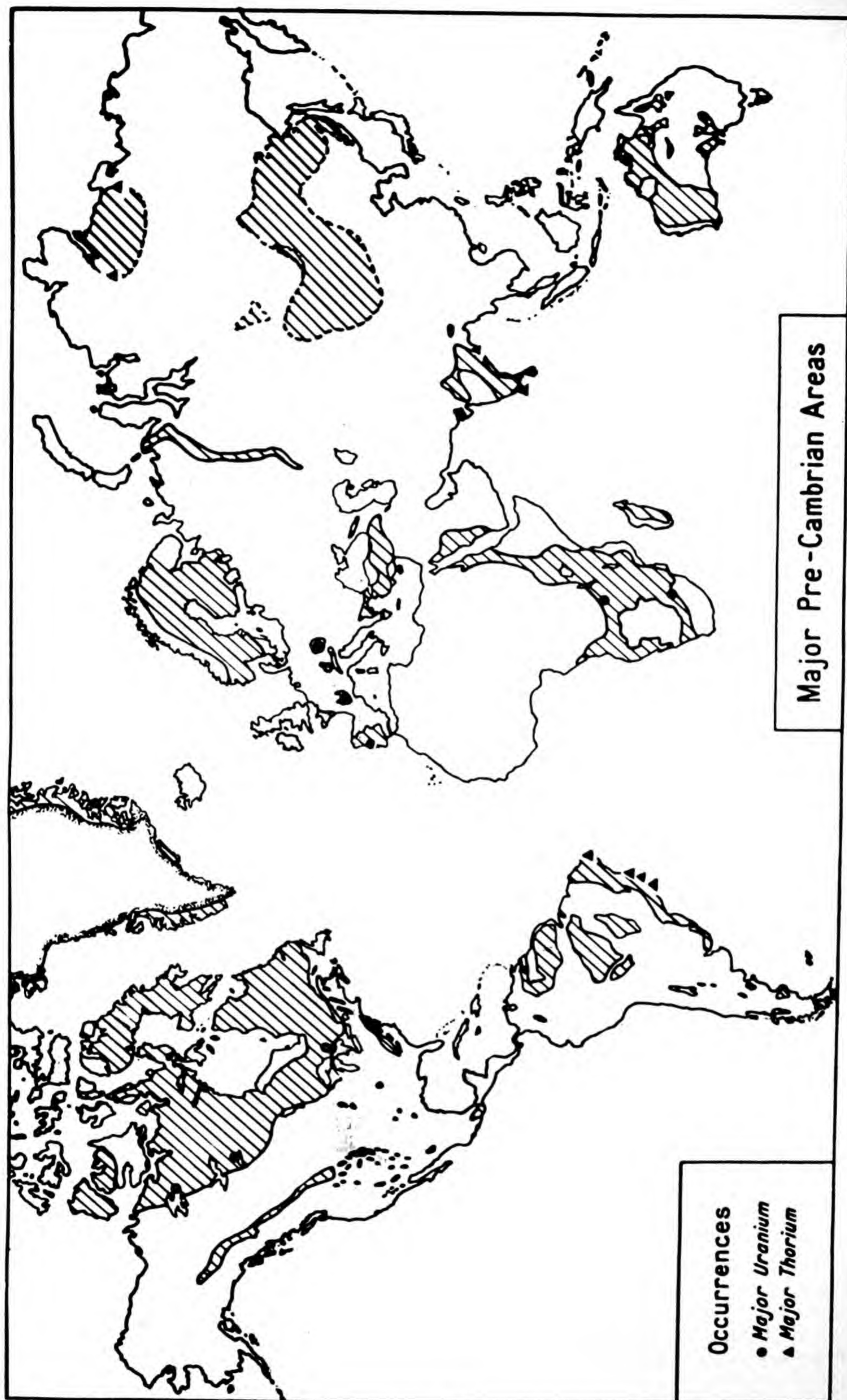


FIG. 1.1. Ancient rock areas.



Rankama and Sahama (1950) place uranium in abundance slightly above the lower third of the list of elements, with thorium in a somewhat higher position. Uranium (4 gm/ton) is considered to be about as widespread as hafnium, arsenic (5 gm/ton) and beryllium (6 gm/ton), while thorium (11.5 gm/ton) is less widespread than cobalt (23 gm/ton), lead (16 gm/ton) and gallium (15 gm/ton). The abundance of uranium in the earth's crust is estimated by Fleischer (1953) to be 0.0002%, or about equal to tungsten or tantalum. Urey (1952) indicates that uranium is the least common element in the earth, having an atomic abundance of 0.0002 (silicon abundance = 10,000).

It appears that rocks high in magnesium, aluminum, and iron (mafic type) are low in uranium, containing about 0.3 part per million. In contrast, rocks at the alkali end of the normal igneous rock series such as granite contain about 5.0 ppm uranium. The tendency of uranium to favor alkali-type magmas is further emphasized by analyses of Colorado Front Range rocks impoverished in calcium, but rich in alkalis. These contain as much as 100 ppm uranium, above the average for a calcium-alkalic granite. Larsen and Phair have indicated (1954) that not only end-stage granitic rock, but end-stage calcium-magnesium rich rocks as well, may show an increase in uranium. Since the original amount in the latter is low, presumably the total increment would be less.

An illustration of end-stage concentration may be an unusual alkali-rich granite in northern Nigeria mentioned by C. F. Davidson (GC 761), with 0.33%  $\text{Nb}_2\text{O}_5$ , 0.012%  $\text{U}_3\text{O}_8$ , and 0.03%  $\text{ThO}_2$ . The productive mineral is pyrochlore, with 41.1%  $(\text{Nb,Ta})_2\text{O}_5$ , 3.1%  $\text{U}_3\text{O}_8$ , and 3.3%  $\text{ThO}_2$ . The operation of the deposit depends upon the ability to successfully produce niobium.

**Accumulation in provinces.** Certain fairly wide areas of the earth's crust show concentrations of particular mineral deposits. Many deposits of tungsten are concentrated in one portion of China. Tin is found throughout a wide area in Bolivia and northern Argentina. A belt of silver deposits occurs in Mexico. Lead-zinc deposits favor the central part of the Mississippi Valley. Such areas are frequently referred to as metallogenic provinces.

The boundaries of a province may be ill-defined, but in general the salient features are recognized by most authorities. It may cover a large part of a continent or it may be restricted to a few hundred square miles. Many complexities of mineralization are included beyond the geographic localization of a metallic element.

The concept of metallogenic provinces aids in establishing regional features which govern deposits of a particular metal. It also establishes boundaries within which the likelihood of added mineral discovery is greater. Likewise, the concept facilitates the accumulation of knowledge of individual deposits and the application of local experience to a broader region.

titles and authors of the Geneva Conference Papers is given at the end of the book, pp. 277 ff.



A number of important metallogenic provinces of uranium and thorium exist in different parts of the world (Fig. 1.2). One such province would be the belt which involves at least eight states in the western United States and extends from southern Arizona and New Mexico northward to the Dakotas and Montana. Other uranium provinces would be the western Canadian Shield and the shield area of southern Africa. Two thorium provinces would be the coastal region of eastern Brazil and the peninsula of India. Joachimsthal in Czechoslovakia is a center in a small uranium province, and it seems likely that the Ferghana region of the U.S.S.R. lies in another province.

Uranium-rich provinces are believed to persist through long periods of geologic time. Regions result in which considerably different types of deposits form—but all of the same metal. It has been suggested by Klepper and Wyant (GC 14) that uranium provinces may be related to original inhomogeneities in the earth's crust. In such places, from geologic age to geologic age the interplay of mineral-forming and mountain-making processes tends to undergo repetition.

The processes of generation, internal adjustment, emplacement, and crystallization of a molten magma during mountain-forming may accentuate crustal inhomogeneities. Since the final fractions of a magma to crystallize are apt to be higher in uranium, mountain-forming processes may cause the concentration of uranium in certain rock types. A magma rich in uranium may hold the metal in coarsely crystalline pegmatite dikes and in various granular plutonic masses or allow it to escape in hot aqueous solutions to form vein-type deposits.

**Ages of deposition.** Broadly considered, age data of two general types apply in geological interpretation. On the one hand there is a tremendous accumulation of information based primarily upon fossil evidence, but combined with stratigraphic correlation, which has been built up by painstaking programs of field and laboratory study (Fig. 1.3). On the other hand there is the determination of absolute age which is based upon the laboratory application of various aspects of radioactive disintegration applied to specimens collected in the field. The first provides a relative sequence; the second more definitely supplies years.

The recent rapid evolution of laboratory techniques has made possible the determination of absolute age in a number of ways. Among the methods usually mentioned, the determinations of the lead-uranium ratios for specimens of uraninite or pitchblende from various well-known uranium deposits furnish age information of considerable interest. The entire subject is reviewed and many determinations given in the text *Nuclear Geology* edited by Henry Faul (1954). With a few exceptions, the absolute ages shown for a few significant deposits outlined in Table 1.1 are from this text.

Notwithstanding the excellent progress which has been made in absolute age determinations, possible errors constitute a major factor in current study. One particular basic difficulty may also exist which requires clarification. Stieff and Stern (GC 298) conclude that two types of lead are recognized in



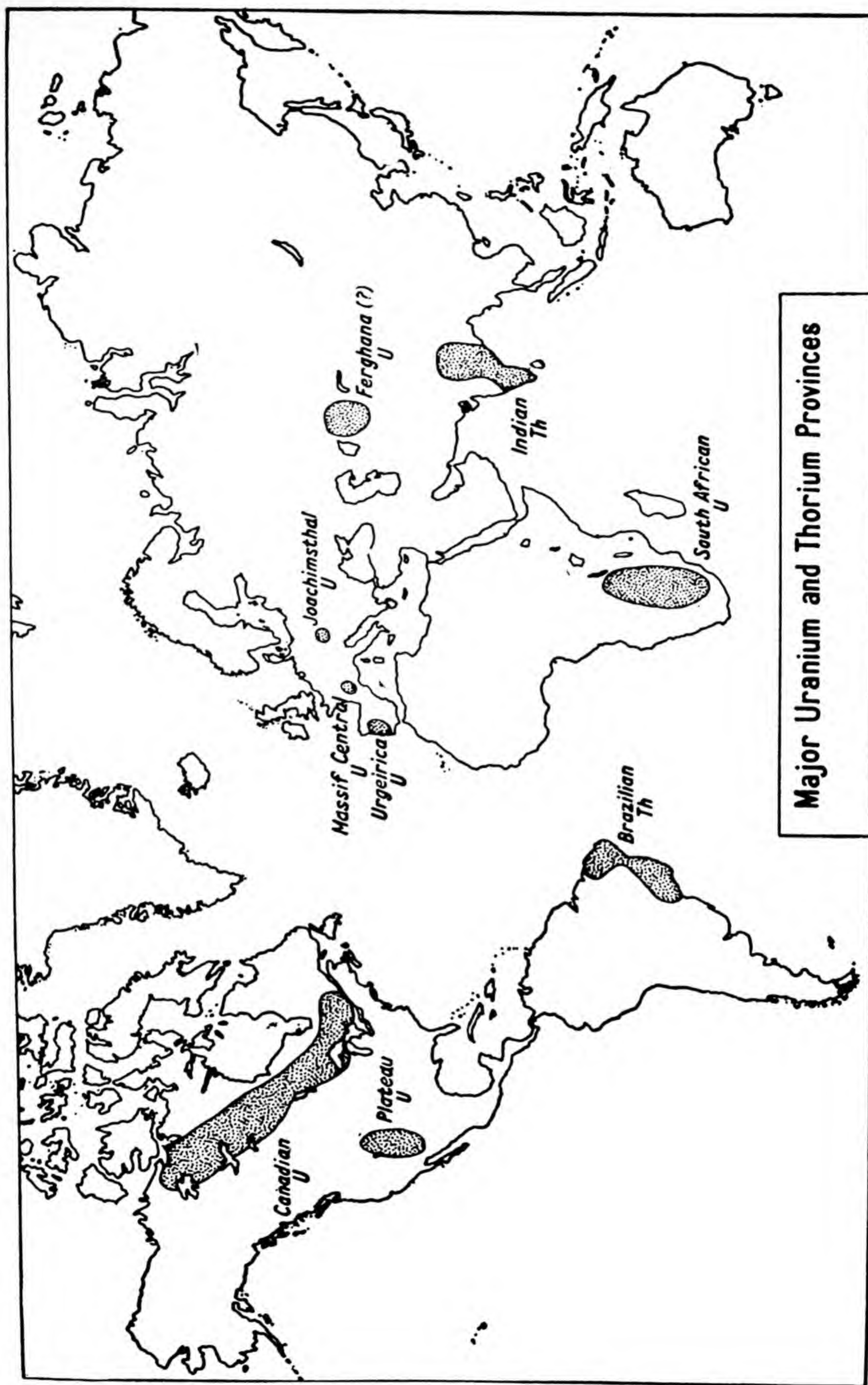


FIG. 1.2. Principal metallogenic provinces. Limited areas of the earth contain groups of deposits.

<b>Cenozoic</b> 72	<i>Pleistocene 2</i>	
	<i>Pliocene 10</i>	
	<i>Miocene 15</i>	
	<i>Oligocene 10</i>	
	<i>Eocene 25</i>	
	<i>Paleocene 10</i>	
	<b>Mesozoic</b> 130	<i>Cretaceous 55</i>
<i>Jurassic 40</i>		
<i>Triassic 35</i>		
<b>Paleozoic</b> 310	<i>Permian 40</i>	
	<i>Carboniferous</i>	<i>Pennsylvanian 40</i>
		<i>Mississippian 30</i>
	<i>Devonian 35</i>	
	<i>Silurian 25</i>	
	<i>Ordovician 60</i>	
	<i>Cambrian</i>	<i>Late 20</i>
		<i>Medial 20</i>
		<i>Early 40</i>
<b>Pre-Cambrian</b>		

FIG. 1.3. Geological time scale. Numbers refer to millions of years. REFERENCES: M. Kay, *Geol. Soc. Am. Memoir* 61: 665-684 (1955); A. Holmes, *Trans. Geol. Soc. Glasgow* 21 (1): 117-152 (1947).



TABLE 1.1. ABSOLUTE AGE DETERMINATIONS ON SELECTED URANINITE FROM COMMERCIAL DEPOSITS

Locality	Age in Millions of Years	Host Rock
<i>Colorado Plateau</i> <sup>a</sup>		
Temple Mountain, Utah		
Camp Bird mine, urano-organic ore . . . .	80 ± 8	Triassic
White Canyon, Utah		
Happy Jack mine . . . . .	42 ± 4, 65 ± 6	Triassic
Monument Valley, Arizona		
Monument No. 2 mine . . . . .	70 ± 7, 85 ± 8, 100 ± 10	Triassic
<i>Czechoslovakia</i> <sup>b</sup>		
Joachimsthal . . . . .	220, 145	Paleozoic
<i>Belgian Congo</i> <sup>c</sup>		
Shinkolobwe . . . . .	630	Pre-Cambrian
<i>Canada</i>		
Great Bear Lake <sup>d</sup>		
Eldorado mine . . . . .	1400	Pre-Cambrian
Beaverlodge area <sup>e</sup>		
Ace mine . . . . .	1820	Pre-Cambrian
Martin Lake mine . . . . .	1110-1670	
Eagle mine . . . . .	1430-1700	

<sup>a</sup> L. R. Stieff and T. W. Stern, in H. Faul (Ed.), *Nuclear Geology: A Symposium on Nuclear Phenomena in the Earth Sciences* (John Wiley & Sons, Inc., New York, 1954), p. 264.

<sup>b</sup> A. O. Nier, *ibid.*, p. 267.

<sup>c</sup> A. O. Nier, C. B. Collins, R. M. Farquhar, and R. D. Russell, *ibid.*, p. 270.

<sup>d</sup> C. B. Collins, A. H. Lange, S. C. Robinson, and R. M. Farquhar, "Age Determinations for Some Uranium Deposits in the Canadian Shield," *Proc. Geol. Assoc. Canada*, 5:15-41 (1952).

<sup>e</sup> C. B. Collins *et al.*, *Mineralogy of Uranium Deposits*, Geological Survey of Canada, Bulletin 31, 1955.

studies of uranium ores from the Colorado Plateau. One is lead derived since the uranium mineral was deposited and the other represents original radiogenic lead present at the time of deposition.

A number of absolute ages determined on uraninite or pitchblende samples appear to be consistent with each other and also with established mineralogical and geological observations. For example, ten age determinations of Shinkolobwe uraninite from the Belgian Congo by Nier (1939) show a range of 582 to 676 million years, with an average of 631 million years. Collins, Farquhar, and Russell (1954) give five determinations on similar samples from the same locality, with a range of 612 to 655 million years and an average of 629 million



years. Thus an age of some 630 million years would seem reasonable for Shinkolobwe uraninite.

On the other hand, Nier (1939) records, in addition to the above, determinations on two specimens, one containing an unnamed secondary mineral, the other curite, both of which at Shinkolobwe are commonly derived from uraninite. Ages given are in excess of 900 million years. Since it must be assumed that these specimens would be younger than the uraninite from which they were derived and not older (as given), the determinations were omitted from the average.

Robinson (1955) has published a series of age determinations based upon an extended study of specimens from the general region in the vicinity of the Beaverlodge development in Saskatchewan, Canada. Determinations reported include a considerable number of specimens collected on various levels of the Ace mine and represent different portions of the deposit. As a result of this study, it would appear that the period over which mineralization must have taken place in the region is remarkably long, representing an interval on the order of 1300 million years. Age differences are found in the same deposit. Within the Ace mine, on the basis of age determinations, a pitchblende zone rich in chalcopyrite east of the mine shaft is considerably younger than another pitchblende-bearing zone west of the shaft.

**Significant mineralogical features.** Studies of uranium and thorium minerals emphasize several features important in the interpretation of natural occurrence. Major differences in regional distribution may be attributed to the character of the minerals formed by the two elements. Minerals resulting from the replacement of uranium-vanadium ores in the sedimentary strata of the Colorado Plateau are a measure of the degree of oxidation of deposits. The urano-organic association furnishes important data on the mechanism of emplacement of uranium in certain sediments. Rare earth complexes containing uranium and thorium, long thought to be mineralogical oddities, have emerged as important source materials. Uraninite, the leading uranium mineral found in multitudinous localities, provides a unique story of time relations and mineral genesis.

A selected group of the more significant or common minerals of uranium and thorium is shown in Table 1.2. Although thorium is more abundant as a rock constituent than uranium, there are only six distinct minerals known with thorium as an essential component. The common ore minerals monazite and xenotime are highly variable in thorium content. In contrast, about seventy minerals are significant for uranium. However, many minerals not listed as thorium compounds, according to the chemical formula, at times contain thorium as a vicarious constituent.

In the list shown in Table 1.2, oxides and silicates are shown for both elements, but here the parallelism between the minerals of the two elements



TABLE 1.2. SELECTED MINERALS OF THORIUM AND URANIUM

	Uranium	Thorium
Oxides	Uraninite (var. pitchblende), $\text{UO}_2$	Thorianite, $\text{ThO}_2$
Hydrous oxides	Gummite, $\text{UO}_3 \cdot n\text{H}_2\text{O}$ Becquerelite, $2\text{UO}_3 \cdot 3\text{H}_2\text{O}$	
Multiple oxides	Brannerite, $(\text{U}, \text{Ca}, \text{Fe}, \text{Th}, \text{Y})_3\text{Ti}_5\text{O}_{16}$  Davidite, $(\text{Fe}, \text{Ce}, \text{U})(\text{Ti}, \text{Fe}, \text{V}, \text{Cr})_3(\text{O}, \text{OH})_7$	Yttrocrasite, $(\text{Y}, \text{Th}, \text{U}, \text{Ca})_2(\text{Ti}, \text{Fe}, \text{W})_4\text{O}_{11}$ Zirkelite, $(\text{Fe}, \text{Th}, \text{U}, \text{Ca})_2(\text{Ti}, \text{Zr})\text{O}_5$
Silicates	Coffinite $\text{U}(\text{SiO}_4)_{1-x}(\text{OH})_{4x}$	Thorite, $\text{Th}(\text{SiO}_4)$
Hydrous silicates	Uranophane, $\text{CaO} \cdot 2\text{UO}_3 \cdot 2\text{SiO}_2 \cdot 6\text{H}_2\text{O}$ Beta-uranotile, $\text{CaO} \cdot 2\text{UO}_3 \cdot 2\text{SiO}_2 \cdot 6\text{H}_2\text{O}$ Sklodowskite, $\text{MgO} \cdot 2\text{UO}_3 \cdot 2\text{SiO}_2 \cdot 6\text{H}_2\text{O}$	Thorogummite, $\text{Th}(\text{SiO}_4)(\text{OH})_{4x}$
Hydrous phosphates	Autunite, $\text{CaO} \cdot 2\text{UO}_3 \cdot \text{P}_2\text{O}_5 \cdot 8\text{H}_2\text{O}$ Torbernite, $\text{CuO} \cdot 2\text{UO}_3 \cdot \text{P}_2\text{O}_5 \cdot 8\text{H}_2\text{O}$	
Anhydrous phosphates		Monazite, $(\text{Ce}, \text{Y}, \text{La}, \text{Th})\text{PO}_4$ Xenotime, $\text{Y}(\text{PO}_4) + \text{Th}$
Hydrous arsenates	Zeunerite, $\text{CuO} \cdot 2\text{UO}_3 \cdot \text{As}_2\text{O}_5 \cdot 8\text{H}_2\text{O}$ Carnotite, $\text{K}_2\text{O} \cdot 2\text{UO}_3 \cdot \text{V}_2\text{O}_5 \cdot 3\text{H}_2\text{O}$ Tyuyamunite, $\text{CaO} \cdot 2\text{UO}_3 \cdot \text{V}_2\text{O}_5 \cdot 8\text{H}_2\text{O}$	
Hydrous sulphates	Zippeite, $2\text{UO}_3 \cdot \text{SO}_3 \cdot n\text{H}_2\text{O}$ Uranopilite, $6\text{UO}_3 \cdot \text{SO}_3 \cdot n\text{H}_2\text{O}$ Johannite, $\text{CuO} \cdot 2\text{UO}_3 \cdot 2\text{SO}_3 \cdot 7\text{H}_2\text{O}$	
Carbonates	Schroeckingerite, $3\text{CaO} \cdot \text{Na}_2\text{O} \cdot \text{UO}_3 \cdot \text{CO}_2 \cdot \text{SO}_3\text{F} \cdot 10\text{H}_2\text{O}$	
Organic compounds	Urano-organic complexes—Mixture of hydrocarbon with U, Th, and rare earths. Thucholite (Carburan)	

ends. Uranium is found in a wide variety of chemical compounds, whereas thorium shows a distinct affinity for rare earth oxides or phosphates and an antipathy to occurrence in the hydrous minerals. Even the parallelism in the case of uraninite and thorianite is only one of classification, since uraninite is an abundant uranium mineral, while thorianite as a source of thorium is either uncommon or rare.

**Uraninite and pitchblende.** Although uraninite has been found in nature in solid masses of oxide reported to measure ten feet across and to weigh twenty tons (Buttenbach, 1925), such occurrences are rare and specimens only inches across may be considered collector's items. Uraninite is the most widely reported of the uranium minerals. The mineral is ordinarily massive, although remarkable rounded (botryoidal) surfaces are occasionally found in openings along veins. The curved patterns attributable to this structure may persist even to microscopic dimensions and have been observed in pitchblende synthesized in the laboratory. The aggregates of crystallites may exhibit curved and rounded structures observable under the microscope although the crystallite dimensions themselves may be less than a micron (Robinson, 1955).



Pitchblende is considered in the seventh edition of Dana's *System of Mineralogy* as a finely crystalline variety of uraninite. It is suggested by Cohen (1953), on the basis of X-ray study, that the term be applied to aggregates of crystallites less than  $10^{-3}$  cm in size. Robinson (1955) points out that crystallite dimensions below  $10^{-3}$  cm prevail in much of the vein material in the Canadian Northwest where the term pitchblende is generally applied.

**Multiple oxides: brannerite and davidite.** As found in nature both of these minerals are believed to have suffered from autodestruction. Distinct crystals with well-formed outlines of crystal faces, as illustrated by Bannister and Horne (1950), are internally devoid of regular atomic arrangement and fail to yield the usual X-ray diffraction patterns of crystalline material. Such minerals, which constitute a considerable group, are described as *metamict*. Brannerite and davidite appear to be the only two metamict uranium minerals which are found in abundance.

The widespread distribution of brannerite through the Mississagi quartzite in the Blind River region of Ontario, Canada, and the occurrence of davidite as an ore mineral at Radium Hill in South Australia, have attracted attention to these two minerals.

**Oxidized uranium minerals.** Ellsworth (1932) describes a specimen of uraninite from Villeneuve, Canada, in which the percentages of Pb,  $\text{UO}_3$ , Th, Ca,  $\text{SiO}_2$ , and  $\text{H}_2\text{O}$  increase with alteration, and U,  $\text{UO}_2$  and rare earths decrease. Kidd and Haycock (1935) noted a somewhat similar progressive oxidation in the pitchblende of Great Bear Lake.

A more obvious effect is the colorful replacement of black pitchblende by bright orange curite, green torbernite, yellow autunite, or other minerals as observed in uranium ores. The minerals produced by this change are generally considered to be formed in the zone of oxidation above the water table and are referred to as the oxidized uranium minerals.

As pointed out by Gruner (1954), secondary uranium minerals occur as relatively insoluble chemical combinations particularly in arid regions. The acid sulfate radical, released by the solution of pyrite, profoundly influences its environment. Uraninite is easily oxidized to form uranyl ( $\text{UO}^{2+}$ ) minerals which in protected places may become the somewhat water-soluble basic sulfates such as yellow uranopilite, yellow zippeite, and apple-green johannite. These minerals, for example, form on the walls of drifts in the Happy Jack mine, Utah, where just enough moisture condenses to supply the necessary  $\text{H}_2\text{O}$ , but not enough to carry the uranium away as the highly soluble uranyl sulfate.

In the Happy Jack mine if vanadium had been present in the unoxidized ores, it is likely that the more insoluble carnotite and tyuyamunite would have formed rather than the sulfates. In the majority of the Plateau deposits,



vanadium is common; hence the basic sulfates are relatively rare in spite of the abundance of pyrite and its easy oxidation.

If no vanadium is present in the unoxidized ores, no oxidized uranium-vanadium minerals will be found. Under these conditions, the hydrous phosphates (autunite and torbernite) and the corresponding hydrous arsenates will form and probably will appear on or near the outcrops.

Schroeckingerite, the complex uranium carbonate, is precipitated as an efflorescent salt only near the surface at Lost Creek, Sweetwater County, Wyoming (Page, 1950). In a trench filled with water, Wyant (1952) notes a concentration of the yellow mineral just above the water line.

In the Rum Jungle area of northern Australia, radioactivity has been found associated with a fluctuating water table which varies from the grass roots during the wet monsoon season to a depth of 200 feet (Fisher and Sullivan, 1954) at the end of the dry season. Laterite formed by the tropical weathering of rocks containing aluminum and iron appears susceptible of the accumulation of radioactivity under such conditions. The hydrous iron oxide of the laterite is believed to adsorb uranium. Laterite areas have been observed to yield high radioactivity in contrast to other rocks in air-borne surveys. Presumably, uranium previously dissolved from underlying rocks by the ground water is taken up by the laterite. While commercial deposits are not formed in this way, the mechanism is of interest.

Until 1952 the Salt Wash sandstone member of the Morrison formation had been considered to yield only carnotite and other oxidized minerals. At that time a mass composed largely of uraninite amounting to 1000 lbs and assaying about 64%  $U_3O_8$  was described by Rasor (1952) from the Grey Dawn mine on the southeast flank of the La Sal Mountains near the Colorado line, Utah. A primary vanadium mineral was found associated with the uraninite, and both occurred in the Salt Wash sandstone. Ores in which the uranium is fixed in uraninite, and the uranium mineral coffinite associated with a vanadium mineral, are now found extensively in the Salt Wash sandstone (GC 295). In such ores the vanadium-uranium ratio varies from 15:1 to 1:1. It is also recorded that the ore is almost without exception associated with coalified wood or other carbonaceous material.

The primary ores are stable in reducing environments and generally remain without change as long as they are below the water table (GC 295). However, on the Colorado Plateau, deformation of strata since the deposits were formed has frequently resulted in changes of position of individual deposits with respect to the water table. As a result, many deposits have been elevated above the water table for a long time, and the processes of oxidation have changed the original uraninite, coffinite, and associated vanadium minerals to carnotite. Study has shown that intermediate stages also exist in which other minerals form. In fact, the mineral assemblage of the



ores in the Salt Wash sandstone has been found to furnish an index to the degree of oxidation.

**Thorium silicates.** Frondel (GC 302) has submitted a review of the mineralogy of thorium. While thorite ( $\text{ThSiO}_4$ ) as a pure compound is readily synthesized, the composition of the natural mineral is greatly modified by the entrance of other elements into solid solution, notably U, Fe, Ca, rare earths, and P. The mineral is also subject to secondary alteration which may result from loss of regular crystalline structure owing to internal emission and absorption of alpha particles. This structural disintegration is accompanied by chemical alteration which includes hydration and some leaching of Si. No fewer than fourteen different minerals described as distinct species are now known or suspected to be identical with thorite or its variant, thorogummite.

Uranium differs from thorium as it may occur in large amounts in hydrothermal deposits which form at relatively low temperatures. Large amounts of uranium can be lost during oxidation by solution in meteoric circulation, particularly in acid waters, whereas the primary compounds of thorium, being chemically stable and quite insoluble during the weathering cycle, tend to accumulate in detrital residues. Soluble salts of thorium hydrolyze readily to insoluble hydrous oxides.

**Thorium phosphates.** There is a considerable contrast between the hydrous phosphates of uranium—autunite and torbernite—and the anhydrous phosphates of thorium—monazite and xenotime—which contain thorium as a variable constituent. The first occur as weathering products comparatively close to the surface and are destroyed by the processes of erosion. The second may occur in veins in igneous rocks from which they may be eroded, transported for many miles, and redeposited in placers. Small angular crystals which are frequently found in the placers indicate the resistant qualities of the thorium minerals. Both monazite and xenotime are characterized by high specific gravity, hardness, and general stability.

**Urano-organic mineralization.** A subject of considerable interest is the association of uranium with lignite as in northwestern South Dakota; with petroliferous material as found on the San Rafael Swell; with carbonaceous shale as in Tennessee; in coal as in Wyoming; together with the long-established existence of the urano-organic mineral thucholite. Inorganic uranium minerals are also frequently found associated with plant debris in the strata of the Colorado Plateau. Remarkable replacements of fossil wood by uraninite and other uranium minerals are occasionally found.

Breger and Deul (GC 49) conclude that uranium is not genetically associated with carbonaceous substances, but is collected by these substances during its migration. It is essential for an organo-uranium association to have an external source of uranium, a transporting medium, and organic matter. In areas of the Colorado Plateau, two masses of coalified wood in close prox-



imity may be either uraniferous or nonuraniferous depending upon the course of uranium-bearing solutions. Aside from minute traces, uranium in petroleum is believed to be due to the ability of certain petroleum constituents to pick up and carry the element. Where large amounts of uranium are present in organic association, the relationship is abnormal and probably indicates addition from outside sources.

**Thucholite.** Thucholite, which has a synthesized mineral name proposed by Ellsworth (1928) indicating the chemical constituents *th* (thorium), *u* (uranium), *c* (carbon), and *ho* (water), combined with *lite* as a mineral termination, was first recognized in the vicinity of Parry Sound, Ontario, Canada. It has since been reported in the hypogene vein deposits at Boliden, Sweden; Moonta, South Australia; Isle of Man; near Deerfield, Saskatchewan, Canada; and near Placerville, Colorado. It is also found in the gold-bearing conglomerates of the Witwatersrand, South Africa, and in similar strata near Blind River, Ontario, Canada.

Uranium-bearing hydrocarbons of the thucholite type occur as lenses and fracture fillings in a fault zone at Placerville, Colorado, and replace sedimentary rocks adjacent to the fault zone. The uranium of the veins is limited to masses of hydrocarbons and minor amounts of autunite and uranophane. Coffinite and pitchblende have been detected by X-ray study of hydrocarbon.

Chemical analyses of the ash of the hydrocarbon show a range in uranium content from 0.034% to 9.8%. The elements chromium, cobalt, copper, molybdenum, nickel, lead, vanadium, and yttrium, which are consistently present, suggest a relationship to oil rather than coal.

The association of the uranium-bearing hydrocarbon with base metal sulfide minerals (chalcopyrite, bornite, sphalerite, tetrahedrite, tennantite, and galena) and with minor molybdenum and cobalt sulfides strongly supports the hypothesis that hydrothermal solutions were active in the genesis of the deposit.

### MECHANISMS OF TRANSPORT AND DEPOSITION

**The role of fluids.** Within the earth's crust, the evolution of fluids from molten rock provides a mechanism of transport whereby metallic ions of various types may be removed from widely disseminated distribution and placed in a position for accumulation in deposits. As observed around vents yielding escaping gases and solutions, surface incrustations contain elements ordinarily associated with metallic ore deposits.

One of the most significant uranium deposits from the standpoint of interpretation of fluid origin is located at Marysvale, Utah. Here, volcanic rocks in great profusion flowed out upon sediments along the western border of the Colorado Plateau in late Tertiary time. Both the flows and the sediments



were invaded by intrusive masses, some several miles across. The area was partially eroded. Still later, outpourings of siliceous lava penetrated the earlier rocks. These lava eruptions were accompanied by an outpouring of thermal solutions some of which deposited uranium. Concentrations of pitchblende, along veins believed to be derived from these solutions, furnish deposits of uranium at Marysvale, which have been mined since their discovery in the winter of 1948-1949 (Kerr, Brophy, Dahl, Green and Woolard, 1955).

Hot springs at the base of mountains to the north and northeast of Marysvale are radioactive in places. The erosional history of the region also indicates that at one time the lavas formed a cover several thousand feet above the terrain of the present surface at Marysvale. It is reasonable to conceive that the Marysvale veins represent the roots of a pre-existing hot springs area the top of which has been removed by erosion.

Solutions rising from the earth's depths are generally believed to have temperatures of at least several hundred degrees centigrade. Temperatures in deep oil wells, even in sedimentary basins remote from igneous activity, are frequently reported to be 175°C or above.

In contrast to precipitation from hot solution, many minerals may form by precipitation from cold meteoric waters. A number of uranium minerals are particularly susceptible to this form of precipitation. In the Red Desert region of Wyoming, Wyant (1952) has reported the formation of the uranium carbonate schroekingerite as a crust around the rim of a pond. Uranium-bearing pendants have also been observed hanging from the roofs of mine workings, contaminated by uranium-bearing solutions as the dripping and precipitating action forming the stalactites proceeded. In the zone above the water table, as shown in mines, uranium minerals are frequently dissolved from earlier-formed deposits and reprecipitated. In fact, uranium minerals such as carnotite, tyuyamunite, autunite, torbernite, and uranophane are generally considered by their presence to signify the action of ordinary surface solutions.

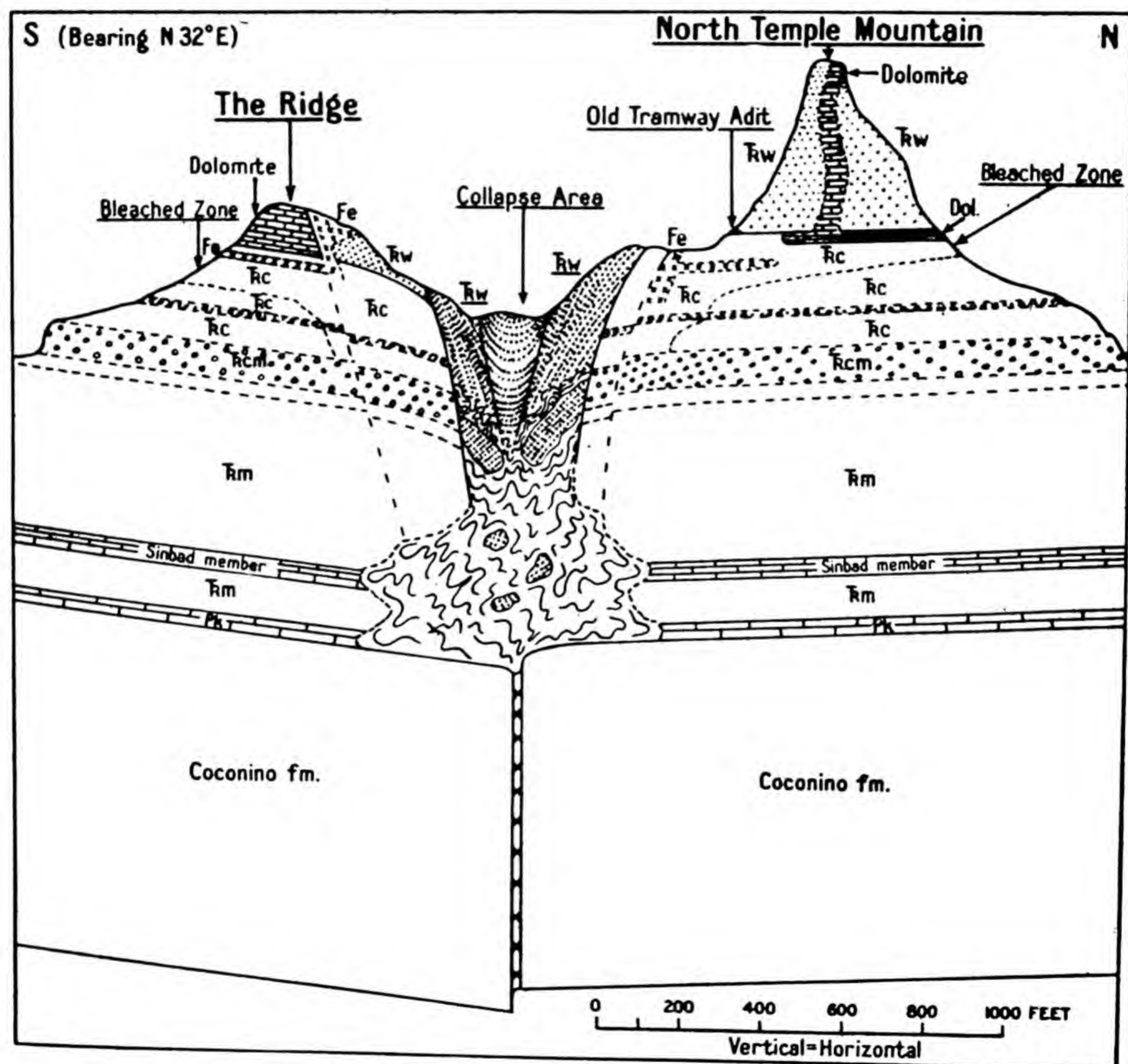
As fluids of magmatic origin rise, they may meet with ordinary ground water in varying degrees depending upon local conditions. In some areas where the magmatic activity is intense, the flow of heated solutions from below may dominate. In areas where magmatic activity is weak or the center is remote, the effects due to rising solutions may be obscured by the prevalence of ground water. This situation may influence interpretation of the origin of uranium deposits.

The widespread distribution of magmas in the earth's crust constitutes a likely general source for uranium and thorium ions. If one overlooks the extent to which ground water may have diluted magmatic fluids, the most readily available original source of uranium or thorium ions appears to lie in the final consolidation of magmas.



**Solution effects: collapse features.** Near Temple Mountain in Utah, heated waters from below appear to have ascended through Triassic formations taking into solution along the way carbonate strata and carbonate portions of otherwise siliceous strata. The solution of the carbonate strata appears to have created caverns into which large masses of overlying beds have collapsed.

The collapse features produced (Fig. 1.4) have been accompanied by a number of solution effects. In these it is believed that the solutions moved upward and that they were heated. One of the most convincing indications of upward transfer is the extensive leaching of calcium, magnesium, and iron from the rocks of the Chinle formation below, and removal upward to be precipitated as



*Kerr, Kelley, Keys, and Bodine, 1955*

FIG. 1.4. Section of Temple Mountain collapse, Utah. Heated solutions appear to have dissolved carbonate in rocks above the Coconino sandstone and caused the collapse of overlying strata.



a Ca-Mg-Fe dolomite and the Fe carbonate siderite in sandstone of the Wingate formation above. In one instance, a great mass of highly siliceous Wingate sandstone is almost completely replaced by dolomite for a thickness of 200 feet. In fact, the replacement has been so complete in many places that silica of the Wingate sandstone has been almost entirely removed (Kerr, Kelley, Keys, and Bodine, 1955).

**Solution effects: volcanic vents (diatremes).** Although the Colorado Plateau is generally looked upon as a large area of stratified sediments, it contains significant examples of igneous activity. The most noteworthy are igneous intrusives of the Henry Mountains, the La Sal Mountains, the Abajo Mountains and other somewhat similar scattered intrusive masses. Also, in some areas, as on the southwest slope of the San Rafael Swell, numerous small dikes and sills are found. In northern Arizona and adjacent parts of New Mexico and Utah some 250 volcanic vents have been observed. These vents exhibit a somewhat restricted form of volcanism in which much of the broken and ejected volcanic material has fallen back into the crater where the eruption took place. They are known as *diatremes*.

Shoemaker (GC 48) states that several uranium deposits occur in diatremes in a number of widely separated localities. The minerals thus far encountered are small podlike concentrations of uranyl vanadates and copper carbonates. The rocks of the diatremes, because of the eruptive forces involved, the number of diatremes to be studied, and the complexity of the deposition, present complex problems of interpretation. In one portion of the diatreme area, however, Shoemaker points to the role of uranium-bearing solutions originating at depth.

**Erosion, transportation, and deposition.** Once a deposit of uranium or thorium becomes part of the surface of the ground it becomes subject to the processes of chemical disintegration and mechanical transport. In general, uranium and thorium respond differently at this stage.

Thorium, as ordinarily found in nature, is less soluble, and as pointed out by Lovering (1955), less subject to disintegration. Thus the processes by which thorium is transported and redeposited are essentially mechanical transfer and gravity accumulation. In Idaho, Mackin and Schmidt (GC 305) have indicated how small crystals of heavy thorium minerals disseminated through parts of the mountainous Idaho batholith have been transferred by stream erosion and concentrated in detrital deposits at lower levels. The same principle of accumulation may apply to many of the deposits in India and Brazil.

In contrast, uranium, unless retained as a minor constituent of an unusually resistant mineral, is dissolved directly or broken into fine particles and dissolved. The products of solution, unless entrapped and precipitated, ultimately find their way through stream courses to the ocean. Thus the lack of records of detrital uranium deposits in recent sediments may be attributed to the chemical nature of the minerals formed rather than to lack of observation.



An exception, if it does exist, would be the uranium of the ancient sediments of the Blind River area in Canada and the Witwatersrand in South Africa. Considerable evidence exists, however, to indicate that even these are not exceptions and that the deposits have originated by precipitation rather than by detrital action.

Davidson (1953) has investigated gold placers from various parts of the world in order to ascertain the effect of mechanical destruction during placer accumulation on the relative amounts of uranium and thorium retained. The study has included gold placer concentrates from New Zealand, the Gold Coast, Sierra Leone, the Belgian Congo, Northern Rhodesia, Canada, Alaska, California, Idaho, Mexico, Colombia, and the U.S.S.R. In the concentrates the mean radioactivity is low. The radioactive minerals identified are mainly monazite, xenotime, thorite, zircon, or complex rare earth oxides. Uraninite was not reported and the uranium detected would be the small amount apt to be found in traces along with thorium. The radioactivity was found to be due essentially to thorium. On the basis of such a study, it is concluded that uraninite lacks the capacity of resistance to abrasion which would make it a placer mineral. Thus the presence of uraninite in ancient pebble accumulations such as the conglomerates of Blind River or the Witwatersrand is in itself evidence of precipitation from solution rather than deposition after mechanical transport.

#### TYPES OF URANIUM AND THORIUM DEPOSITS

**Deposits due to heated fluids.** A large group of deposits are believed to have originated from heated fluids which probably varied from highly compressed vapors to ordinary hot solutions. Uranium and thorium ions taken into solution within the earth's crust terminate their ascent by precipitation in some favorable environment. Often the site of precipitation is a vein or veinlet in a rock mass where uranium or thorium minerals fill fractures. In rare cases a segregation of productive minerals in large masses may be found. Occasionally, small crystals and fine particles may occur disseminated through wall rock.

The type of deposition may be influenced considerably by the depth within the earth's crust that precipitation takes place. Ancient rocks are apt to have been deeply buried during their penetration by solutions. Hence, deposits in such rocks show the effects of precipitation under pressure and at considerable temperature. Younger rocks are more apt to be permeable and to contain openings, but the pressures are less and the temperatures may be lower.

Deposits formed by heated solutions include the effects caused by residual crystallization of extracts from molten magma (pegmatites), disseminations in mixed crystalline rocks, and veins of various types. In the first two types, extreme pressure is a dominant factor, as indicated by phenomenal crystalliza-



tion in pegmatites and by rock flowage accompanying mineralization as shown in mixed rock disseminations. The fractures and broken zones of veins, although the result of rock deformation, lack the solidity of a mass subjected to flowage under extreme pressure or the coarse crystallization of a pegmatite.

**Residual igneous crystallization (pegmatites, migmatites, etc.).** Pegmatites represent remarkably coarse crystallization that follows the solidification of large plutonic rock masses. They are found in greatest abundance in the pre-Cambrian areas of the world. The fluids of the magma that remain after the main mass has solidified force their way along fracture planes into surrounding rocks and into portions of the main pluton already solid. In these natural traps the physical and chemical conditions are ideal for unusual crystal products. At the same time pegmatites are apt to be erratic in shape and distribution and are chiefly considered as sources of feldspar, lithium, beryllium, tantalum, and columbium rather than uranium and thorium.

Pegmatite dikes yield attractive specimens of uranium and thorium minerals. Among the many hundred of dikes known, only a few have offered the possibility of commercial development for uranium or thorium minerals. Exceptional pegmatites, suggesting possible commercial development, have been described at Charlebois Lake, Saskatchewan (Lang, 1952) and Bancroft, Ontario, Canada (Satterly and Hewitt, 1955).

At times residual fluids corresponding in many respects to the fluids which form pegmatites force their way along with portions of the unconsolidated magma into border rocks. The process occurs where pressures are great—well toward the bottom of the earth's crust. Later, after consolidation and the long process of erosion, such rocks ultimately become exposed at the surface. Many examples of so-called injected rocks (mixed rocks or migmatites) may be observed particularly in pre-Cambrian areas (Barth, 1951). Occasionally, mineral deposits are created in such areas. Uranium and thorium deposition found under such circumstances may have many of the characteristics of a pegmatitic occurrence, but it offers the possibility of more widespread distribution.

Large masses and crystals of a complex uranium oxide which is related to davidite have been described by Bannister and Horne (1950) from Mozambique. These crystals may measure as much as a foot across. The deposits are complex in their geological relations, but according to Davidson and Bennett (1950) are unlike pegmatites which are found in the same region. Lenses of ore occur along a shear zone in anorthosite, an unusually calcic host rock for a uranium occurrence. Davidite occurs in scattered crystals in a lens of calcite and more abundantly in a band of scapolite, a complex calcium silicate.

**Radium Hill, South Australia.** The uranium mineral of the ore body at Radium Hill in Australia resembles the davidite of Tete, Mozambique, and the brannerite of the Blind River area, Canada, since in each uranium is found in a metamict mineral of a type foreign to pitchblende veins. Such metamict



minerals would be expected in pegmatites, yet the more recent field descriptions indicate that the ores are not found in pegmatites in any of the three localities. The two davidite occurrences, however, as described may represent a phase not far removed in terms of temperature and fluidity from the pegmatitic stage in the same way that quartz veins may frequently grade into pegmatites. For this reason the Radium Hill occurrence is considered to have been formed under higher pressure and temperature than that of a pitchblende vein; it formed toward the end, and probably below, the pressure-temperature conditions of a pegmatite or migmatite.

**Veins.** Uranium veins represent fracture planes along which uraninite or pitchblende have been precipitated. The fractures are believed to form most frequently where rocks have been subjected to tensional stress. Sizes vary from veinlets of paper thickness to massive veins several feet across. As mined, veins are ordinarily groups of fracture fillings which in the aggregate constitute an economic unit.

Veins are found in a variety of rock types which include normal igneous rocks, recrystallized igneous or sedimentary rocks, and porous sediments. In age of emplacement the uranium mineral in veins may be as young as the uraninite from Marysvale, Utah (ca.  $10 \times 10^6$  years) or as old as pitchblende from the Ace mine north of Lake Athabaska, Canada ( $1820 \times 10^6$  years).

At least three general epochs of uranium mineralization have been recognized (Everhart and Wright, 1953).

1. Pre-Cambrian. *Examples:* Great Bear Lake, Lake Athabaska area, Montreal River (Canada), and Shinkolobwe (Belgian Congo).
2. Paleozoic. *Examples:* Joachimsthal and Johanngeorgenstadt (Czechoslovakia), Wolsendorf (W. Germany), Cornwall (United Kingdom), and Urgeirica (Portugal).
3. Tertiary; Mesozoic. *Examples:* Coeur d'Alene, Colorado Front Range, Marysvale (U.S.A.), and Carrizal-Alto (Chile).

Silica in the form of quartz is seldom absent in uranium veins and is frequently a major constituent. Iron and sulfur are abundant as pyrite. Iron, however, may form ferric oxide, which frequently causes a red stain along veins and in bordering rocks. Calcium fluoride as fluorite is an important constituent of some veins and represents a reaction product between fluorine in the vein-forming fluid and calcium in wall rock along the vein conduit. Calcium carbonate may be present as calcite.

A number of veins and groups of veins have furnished remarkable uranium deposits.



## OLDER URANIUM MINERALIZATION (VEINS)

**Great Bear Lake, N.W.T., Canada.** The most historic uranium-bearing veins in North America are located about twenty miles south of the Arctic Circle on the east shore of Great Bear Lake in Northwest Territories, Canada.

A series of nearly east-west veins cuts a pre-Cambrian complex known as the Echo Bay group. The rocks of the Echo Bay group have been so altered by igneous invasion and hydrothermal processes since their formation that their exact original character has been largely obscured. In general, the group is considered to consist of materials originally fragmental volcanics, stratified sediments, and igneous intrusives.

The veins are vertical or steeply inclined and are ore-bearing at least to a depth of 1800 feet as established by underground workings. Although small amounts of oxidized uranium minerals have been noted in thin films or coatings on fractures near the surface, the uranium has been found almost entirely in pitchblende.

Pitchblende occurs in forms characteristic of deposition in a colloidal state. The rounded botryoidal (grapelike) masses originally gelatinous typify sub-microscopic crystals which have formed concentric aggregates.

**Ace Mine, Lake Athabaska, Canada.** Within the last few years, an extensive uranium-producing district has been developed in the vicinity of Beaverlodge Lake just north of Lake Athabaska, Saskatchewan, Canada. Extending northeasterly from Beaverlodge Lake for a distance of at least ten miles is the St. Louis fault. The fault may be traced across Ace Lake to Raggs Lake and is well marked along the surface by a broad trough which cuts an almost straight line across the rocks of the pre-Cambrian shield.

The St. Louis fault is inclined at about  $50^{\circ}$  to the south and marks a break between the Athabaska series of rocks which lies above the fault plane and the Tazin Group below. The uranium ore occurs as pitchblende in a network of small stringers which underlie and form a band within 200 feet of the fault plane.

The main surface showings were discovered by radioactivity surveys and cut with trenches. They were small and unimpressive as uranium prospects. The decision to institute a drilling program was based upon geological considerations, the most important reason being the proximity of the showing found to a regional fault and the fact that the rocks nearby were poorly exposed.

**Gunnar uranium deposit, Lake Athabaska, Canada.** The Gunnar uranium deposit on the Crackingstone Peninsula of the north shore of Lake Athabaska, Canada, was discovered in the summer of 1952. The deposit lies in an area of pink granite-gneiss considered by Fraser (1954) to be among the oldest rocks of the Canadian Shield (Archean or Proterozoic).



The rocks in which the uranium ores occur have been subjected to an involved sequence of genetic events. The prevailing formation in the district has been mapped as granite-gneiss, a recognizable field unit (Fraser, 1954). The ore, however, occurs in a somewhat different rock type described by Fraser and Robinson (1954) as an albite monzonite. Both rock types retain banded structures and textures suggestive of old sediments. In fact, it is stated that the reworking of old sediments by magmatic melting and subsequent recrystallization may have been involved in their original formation.

The ore occurs in an irregular more or less rounded zone 200 to 600 feet wide and 1100 feet long. Uraninite and uranophane yield uranium and are disseminated through somewhat porous zones in the monzonite. Local high-grade ore zones are related to highly broken areas or zones of brecciation in the monzonite. Rare stringers also carry high-grade pitchblende and iron oxide.

**Shinkolobwe Mine, Belgian Congo.** The uranium deposit at Shinkolobwe is located in the Belgian Congo  $11^\circ$  south of the equator and about equidistant between the two sides of the African continent. Shinkolobwe is situated along the western margin of a broad northwesterly trending arc of folded and faulted pre-Cambrian sediments known as the Katanga synclinorium. The arc is some 200 miles long and in the center 65 miles across. In addition to uranium, several significant copper deposits, together with other metals, the most important of which are cobalt and zinc, occur in this belt.

The mineral associations of Shinkolobwe are remarkable. Some 30 mineral species have been recognized here for the first time. Including the new species, 67 minerals are considered significant in the description of the deposit. Uranium minerals found include 4 oxides, 9 uranates, 4 uranosilicates, 7 uranophosphates, 4 uranocarbonates and a uranomolybdate. At least 11 of the oxidized minerals contain substantial amounts of lead presumably derived from the autodisintegration of uraninite.

In the lower workings, unusual sulfide associations have been encountered. The common occurrence of  $\text{CoS}_2$  and  $\text{NiS}_2$ , each with the crystal structure of pyrite  $\text{FeS}_2$ , and both minerals associated with uraninite is unique. The cobalt mineral, cattierite, and the nickel mineral, vaesite, have also been found, with selenium substituting for sulfur.

The minerals of uranium are distributed in masses, along veins and veinlets in fractures, in seams, and along planes of stratification and at times are even disseminated in strata of the lower part of the Mines series. At depth, the deposits are composed in part of massive uraninite and in part of uraninite mixed with cobalt and nickel sulfides. The uraninite is crystalline and frequently occurs in cubes, a distinct contrast to the botryoidal form frequently observed in pitchblende at Great Bear Lake and Joachimsthal. Exceptional cubes have been found at Shinkolobwe that measure 4 cm along an edge.

Near the surface, uraninite is replaced by the numerous oxidized uranium



minerals. In many cases the uraninite may be observed to have been replaced *in situ*, the entire mass of a vein consisting of oxidized minerals. Elsewhere the migration of solutions along fractures has distributed the oxidized uranium minerals as colorful brown, yellow, or green veinlets.

Monazite is found in small crystals along veins and also in masses. As shown in microscopic study, veinlets of monazite may be observed that penetrate uraninite and hence are believed to have crystallized later.

**Joachimsthal, Czechoslovakia.** The historic veins of Joachimsthal (Jáchymov), Czechoslovakia, and nearby localities have been mined intermittently for centuries. The veins are formed along fractures and appear to vary considerably in thickness while also exhibiting changes in mineralization. Uraninite is the principal uranium mineral. Associated minerals in the veins include native silver, bismuth, cobalt-nickel minerals and sulfides of zinc, copper, and lead (Everhart and Wright, 1953). Large portions of veins are suitably thick or grouped for mining.

At Joachimsthal the wall rock which appears associated with the highest-grade mineralization is schistose pre-Cambrian sediment. In some of the mines, as the veins cut granite at depth, it has been inferred that uranium values diminish. The granite is said to be late Paleozoic in age.

#### YOUNGER URANIUM MINERALIZATION (VEINS)

At least 23 veins are known in the U.S.A. in which uraninite or pitchblende emplacement occurred during or slightly before the Tertiary (GC 20). At the Los Ochos mine, Saguache County, Colorado, Derzay (GC 285) has described a vein occurrence of pitchblende along the Los Ochos fault. The fault cuts the Salt Wash member of the Morrison formation (Jurassic) and the younger Cretaceous formations, Dakota and Mancos, as well. The vein is comparatively narrow in underlying pre-Cambrian granite, but considerably wider in the porous Salt Wash sandstone. The mineralization is at least later than the Salt Wash.

McKelvey, Everhart, and Garrels (see Chapter 3) refer to a mean age of  $60.5 \times 10^6$  years for pitchblende found in veins of the Front Range deposits in Colorado. The pitchblende-bearing veins at Marysvale, Utah, as indicated by Kulp, Bate, and Giletti (1955) appear to be considerably younger ( $10 \pm 2 \times 10^6$  years).

The Cordilleran region of the western U.S.A. is a region in which Tertiary and somewhat older mineral deposition has long been recognized for metallic elements other than uranium. It is also a region in which correspondingly youthful forces of deformation have been active. Thus in many places in the region in Tertiary time, fracture systems have been provided which prob-



ably extend to considerable depths, and at the same time, heated solutions carrying uranium have been available to form deposits.

The veins formed exhibit distinct differences from the older vein types of the Canadian Shield and elsewhere. Clay minerals and sericite are common in veins and along vein walls. Oxidation with the development of secondary minerals is on the whole more abundant. Vein zones and their environs show less evidence of consolidation since mineralization took place.

**Contact deposits.** Two deposits are described by Thurlow (GC 27) in which mineralization appears to be concentrated in small fractures in border rock along an intrusive contact. Although confirmatory age data are lacking, it would seem likely that the emplacement of these deposits would agree with the younger vein group.

Uranium occurs in an argillite series in contact with granite on the Spokane Indian Reservation in northeastern Washington in the U.S.A. Diamond-drill cores show the presence of uraninite and pyrite at depth. Autunite and metatorbernite were mined at the contact. Mineralization extends 40 feet into the argillite series and 25 feet into the granite. Although the original mineralization appears to have occurred in the argillite, it may be related to the granite magma.

A contact deposit is reported from Lander County, Nevada, where uranium minerals occur in fractures along a contact between a quartz monzonite intrusive and bordering metamorphosed sediments consisting of hornfels, quartzites, and phyllites. Autunite and metatorbernite are associated with fine-grained siliceous dikes, vein quartz, and iron oxides in an area of intense silicification.

**Fluorite deposits.** Radioactive fluorite deposits occur on Spors Mountain in the western part of the Thomas Range, Juab County, Utah (GC 23). The amount of uranium in 155 fluorite samples was found to range from 0.003% to 0.33%.

The deposits are found in dolomite of middle Silurian age. Structurally the deposits form oval to irregular pipes, veins, and disseminations. The major deposits are the pipes, which vary considerably in size. The pipes are adjacent to faults or to intrusive breccia bodies. In many instances, the pipes become smaller and lower grade with depth. Uranium is secondarily enriched near the surface because of leaching from upper parts of the deposits and redeposition below.

The formation of the fluorite is attributed to fluorine-rich fluids containing minor amounts of uranium which rose along faults and shattered zones. It is suggested that uranium was originally dispersed throughout the fluorite, perhaps within the crystal structure. Fluorite-forming fluids were probably derived from the same source which yielded abundant topaz in the rhyolites of the eastern half of the Thomas Range.



## URANIUM IN ANCIENT SEDIMENTS

**Blind River area, Canada.** Uranium occurs in ancient ore-bearing sediments in the vicinity of Blind River, north of Lake Huron, Ontario, Canada. The sediments lie at the base of the Mississagi quartzite which in turn rests upon an eroded basement of granite and gneiss. Both sediments and basement are pre-Cambrian, the sediments being classed as Huronian and the basement as pre-Huronian (Joubin, 1954).

The ore is found in a firmly cemented conglomerate consisting largely of quartz pebbles. Surrounding the pebbles is a matrix consisting for the most part of iron sulfide, but containing disseminated grains of radioactive minerals. The conglomerate is distributed along the base of the Mississagi quartzite, which in this region is from 1500 to 3500 feet thick.

**Witwatersrand, South Africa.** Uraninite, with or without thucholite, is reported by Davidson and Bowie (1951) to occur in all the workable gold-bearing conglomerate strata of the Rand. It occurs from the Dominion Reefs at the base of the Witwatersrand system to the top in the Elsburg Reefs and Vetersdorp Contact Reef, a thickness in excess of 25,000 feet. Many reefs that are uneconomic for gold contain a significant amount of uranium. Data are inadequate to compute the uranium content of the Witwatersrand basin as a whole, but it has been estimated to be greater in total amount than that of any similar volume of rock known anywhere in the world (Davidson and Bowie, 1951).

The origin of the Rand gold ore has long been the subject of a major difference of opinion. One group, composed mostly of those engaged in active mining, has considered the gold to be contemporaneous in origin with the conglomerate in which it is found. Another group favors precipitation from heated gold-bearing solutions rising from below and depositing the metal in the porous conglomerate strata.

Davidson and Bowie conclude that the gold and uranium were deposited at the same time, and also that any explanation of origin applicable to one would also apply to the other. This conclusion is based largely upon the observation that the gold and uranium, as shown by many analyses, have been found to vary sympathetically.

It is pointed out by Davidson and Bowie that the uraninite-bearing hydrocarbon of the Rand is essentially identical with thucholitic hydrocarbons produced elsewhere by rising heated solutions.

1. The uranium content of the Rand conglomerate is much greater than may be observed for present day placers.
2. Uraninite is not a placer-forming mineral.
3. Gold and uraninite have been found to crystallize together as the result



of precipitation from heated solutions in veins located in the Belgian Congo, Mexico, and Canada.

4. The complex chemical compositions of the uranium minerals in the basement rocks which encircle the Rand basin preclude their role as a source for the mechanical transportation and deposition of uraninite.

These factors strongly support the theory of rising thermal solutions as the source of the Witwatersrand uranium.

#### THORIUM BY DIRECT CRYSTALLIZATION

Thorium minerals are deposited as direct products of crystallization in pegmatite dikes or thorium-bearing veins. Thorium is also found in accessory minerals formed during the crystallization of igneous masses or as products of recrystallization in metamorphic rocks. Unlike uranium minerals, thorium minerals are not reported as products of crystallization in porous sediments of the Colorado Plateau type, nor do the bituminous sediments appear to yield thorium, notwithstanding the fact that they may be at times rich in uranium. In general, thorium minerals are crystallized under temperatures of several hundreds of degrees centigrade and under pressures that would prevail thousands of feet below the surface. Such conditions favor areas of igneous and metamorphic rocks.

Because of its chemical characteristics, thorium is closely related in occurrence to zirconium, uranium, and rare earth metals. Many alkalic rocks are thought to become enriched in thorium during the process of magmatic differentiation (GC 301).

Pegmatites rarely yield thorium minerals in recoverable amounts. None of those found in the United States have been found to justify economic development (GC 301). None of the Norwegian pegmatites appear likely to produce uranium or thorium ore other than as by-products of feldspar mining (GC 887).

Thorium and rare-earth-bearing veins found in the United States (Fig. 1.5) occur in California, Colorado, New Mexico, Montana, Wyoming, and Idaho. Monazite and thorite are the principal thorium-bearing minerals, but other minerals (bastnaesite, thorogummite, and fluorapatite) are potential sources of by-product thorium in certain places.

Two belts of thorium-bearing rocks appear to follow a northeastward trend across the piedmont of the eastern United States from Alabama to Virginia, a distance of 550 miles, where they join to extend an additional 50 miles northeastward (Fig. 1.5). The thorium is found in monazite, which occurs more abundantly where the rocks have been intensely recrystallized sediments. These intrusives, numerous pegmatite dikes, schists, gneisses, and related





*After Twenhofel and Buck, 1955*

- |                          |                          |                          |
|--------------------------|--------------------------|--------------------------|
| 1 Idaho placers          | 6 Gallinas District      | 12 Palmer area           |
| 2 Mineral Hill District  | 7 Wet Mountains          | 13 Mineville District    |
| 3 Lemhi Pass District    | 8 Powderhorn District    | 14 Eastern monazite belt |
| 4 Deer Creek District    | 9 Bear Lodge Mountains   | 15 Western monazite belt |
| 5 Mountain Pass District | 10 Little Big Horn River | 16 Jacksonville placer   |
|                          | 11 Wausau area           |                          |

FIG. 1.5. Thorium deposits in the U.S.A. A belt of disseminated thorium occurrences in ancient rocks occurs along the Atlantic area.

metamorphic types together constitute a rock complex. Thorium is more abundant where the highest temperatures and pressures prevailed during recrystallization as indicated by the prevalence of such minerals as silimanite, staurolite, and kyanite. Thorium is widely distributed in disseminated monazite crystals (GC 306).

### URANIUM ACCUMULATIONS IN SEDIMENTARY STRATA

The deposits of the Colorado Plateau have furnished the principal source of uranium in the United States. Uranium occurs in many formations ranging in age from late Paleozoic to mid-Tertiary. However, deposits which have yielded significant production are restricted mainly to Triassic strata which include the Shinarump or nearly equivalent conglomerates and the Chinle formation, and Jurassic strata which include the Todilto limestone, Entrada sandstone, and Morrison formation (GC 473).

Until 1951 the bulk of uranium ore produced in the United States was de-



rived from the fluviatile sediments of the Morrison formation. Discovery of uranium in other formations has decreased the proportionate predominance of Morrison production, but in the aggregate the strata of this formation are still the most productive of the Colorado Plateau (GC 474).

In recent years extensive uranium deposits have been developed on the north slope of the Zuni Uplift in northwestern New Mexico in the Morrison formation. Here the ore-bearing unit has been shown to be the equivalent of the Brushy Basin member of the Morrison. Larger deposits occur in relatively coarse-grained sandstone strata where the sandstone is thicker (GC 38).

In addition to the occurrence in the sedimentary strata of the Colorado Plateau, uranium is found in substantial amounts in sediments elsewhere in the United States. These occurrences include deposits of considerable size in Cretaceous sandstones of the Black Hills region of South Dakota and Wyoming; occurrences in sandstone associated with volcanic ash or tuff in Wyoming, Texas, and Nevada; and small deposits in terrestrial sedimentary rocks in Pennsylvania, Oklahoma, New Mexico, and other places (GC 472).

**Stratigraphic distribution.** Great interest has been attached to the stratigraphic distribution of the uranium deposits in sedimentary formations. Several reasons may be given.

In the search for productive uranium deposits, formational units have proved to be an important guide. Thus the Salt Wash member of the Morrison formation and the Shinarump conglomerate near the base of the Chinle formation are two of the most widely surveyed formations of the Colorado Plateau. Elsewhere other formations receive equal scrutiny.

In the interpretation of origin considerable significance has been attached to the fact that a number of formations of widely different age are uranium-bearing. These range in age from Cambrian to Tertiary, although great variability exists in the productivity of different formational units. Such distribution emphasizes the introduction into strata of uranium from sources extraneous to the beds in which the ores are now found. The supply would have needed to move along lines that would intersect strata more or less at right angles.

Not only the uranium-bearing formations themselves but also the strata above are of interest in the interpretation of origin. Fine, ejected and settled volcanic ash or tuff may be found in strata which are not far above at least three different uranium-bearing formations. Leaching of uranium from the ash and deposition in the ore-bearing beds below has been proposed by some as a mechanism of ore deposition on the basis of this stratigraphic situation. Others point out that the situation does not apply uniformly to all formations. In any case, stratigraphic information becomes of interest.

**Structural controls.** The Lisbon Valley anticline is one of the typical folds of the eastern Utah area which has attracted particular attention in uranium exploration.



It is believed that regional structure of the Colorado Plateau influences the distribution of the uranium deposits. Major northwesterly trending, deep-seated lineaments appear to have influenced structural trends, igneous centers, and ore distribution (GC 29).

Although structural lines are in evidence and in a number of places marked deformation may be observed, the Plateau area has been one of greater or lesser stability since pre-Cambrian time. Laramide (Tertiary) deformation is expressed by a number of broad folds and sharp flexures, but over wide areas the sedimentary beds are nearly horizontal (GC 473).

Regional study of the geologic development of the Cordilleran Foreland of the western United States reveals broad-scale structural characteristics which are considered significant in the study of uranium deposits (GC 28). The foreland consists of a series of structurally asymmetric basins separated by folded mountains. Throughout the area many of the faults, folds, and other forms of flexures observed in study of the surface are considered to originate in deformation within the frequently deeply buried underlying pre-Cambrian basement.

Throughout the region, repeated deformation of old structures causes even relatively young Tertiary rocks to be slightly folded and fractured. Repeated deformation along old structures has tended to produce mountain margins bounding basins in which thick sedimentary accumulations result. Such features receive serious consideration in interpreting the conditions of uranium accumulation.

At areas of intersection between trends, pathways for the migration of uranium-bearing solutions are created in greater abundance. It would also seem that solutions carrying uranium ions and originating in the basement tend to come to a focus in such areas.

**Sedimentation features.** Study of the sedimentary features of the Morrison formation (Jurassic) of the Uravan district, Montrose County, Colorado, reveals that the principal uranium-vanadium deposits in the district are restricted to the upper sandstone lenses of the Salt Wash member. Individual lenses are enclosed by relatively impermeable mudstone beds. Hence the sandstone lenses do not form extensive aquifers along which ore-bearing solutions might be expected to migrate on a district-wide basis. It is improbable, therefore, that the ore-bearing sandstone lenses of the Long Park area are continuous with the ore-bearing sandstone lenses in the nearby Club Mesa area (GC 35). The stacking of channels one above another as sedimentation proceeds may produce a formation with highly variable porosity. Such multiple-channel patterns studied in Arizona (Fig. 1.6) indicate the direction in which deposition took place and suggest directions to follow in tracing ore bodies (Lowell, 1955).

Sedimentation features which indicate the direction of original transport are



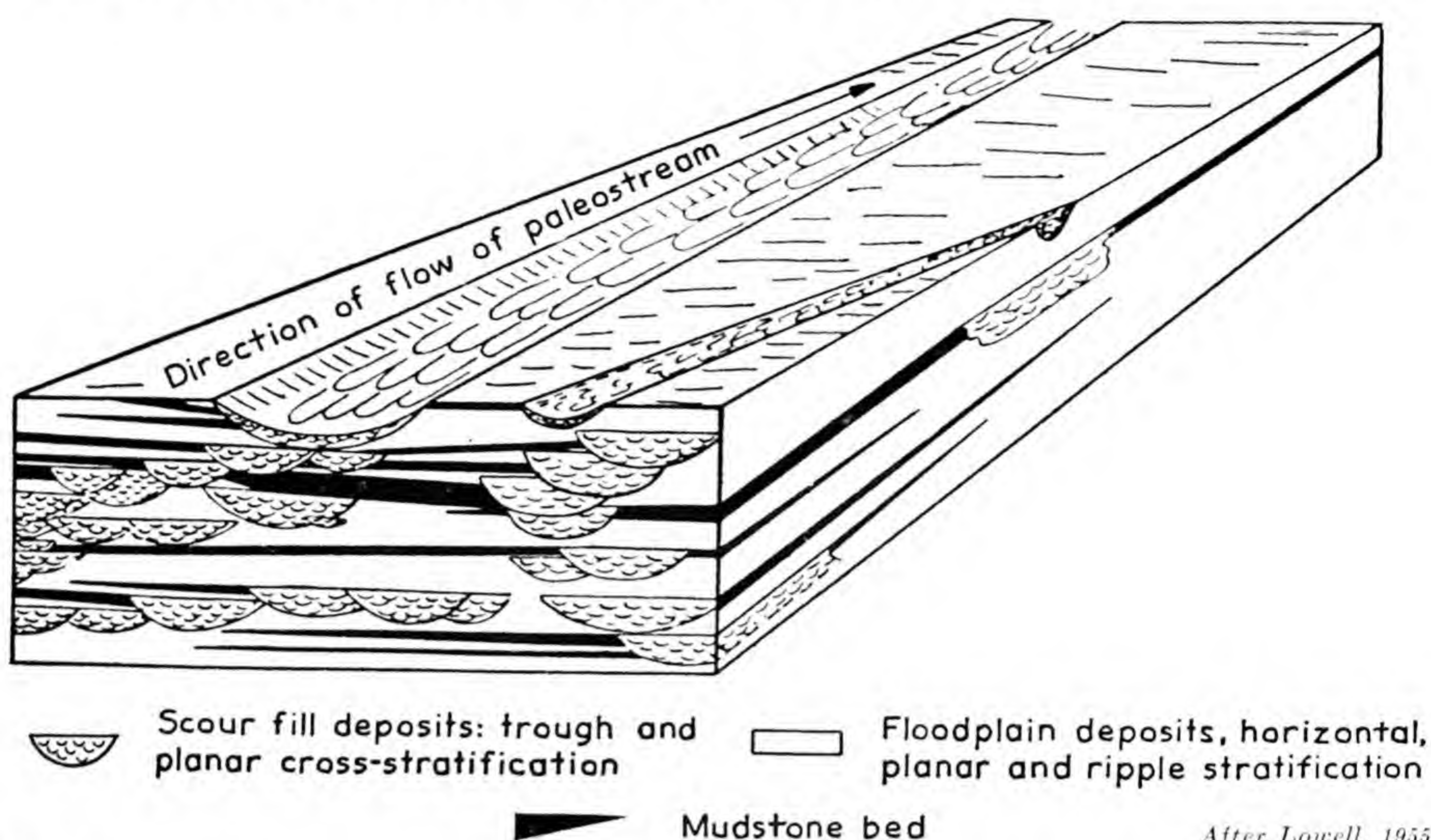


FIG. 1.6. Stacked channels. The diagram shows channels above each other as observed in the Morrison formation in Arizona, U.S.A.

of interest in connection with the study of the continuity and trend of uranium-bearing deposits. Such features have received particular attention in the examination of deposits in sediments in the Colorado Plateau (GC 34).

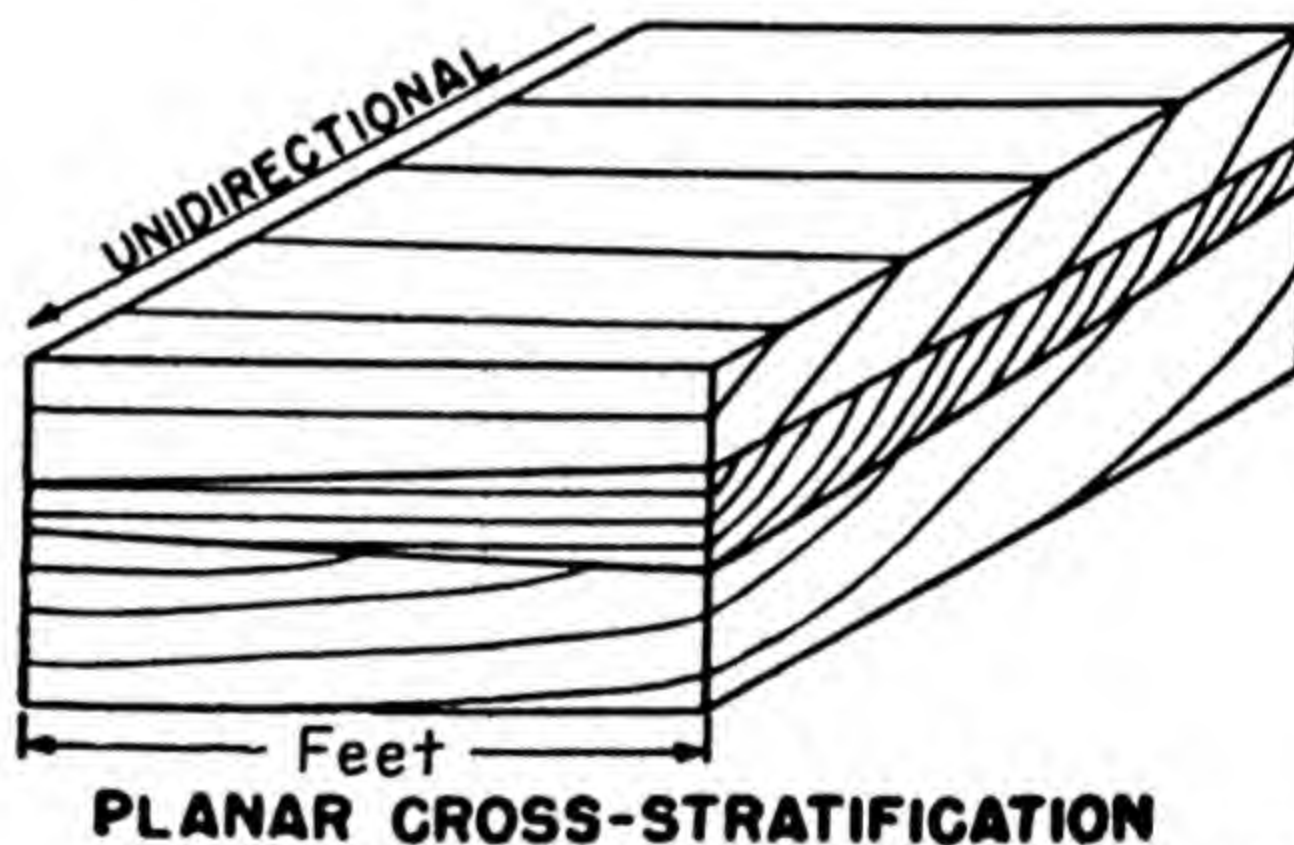
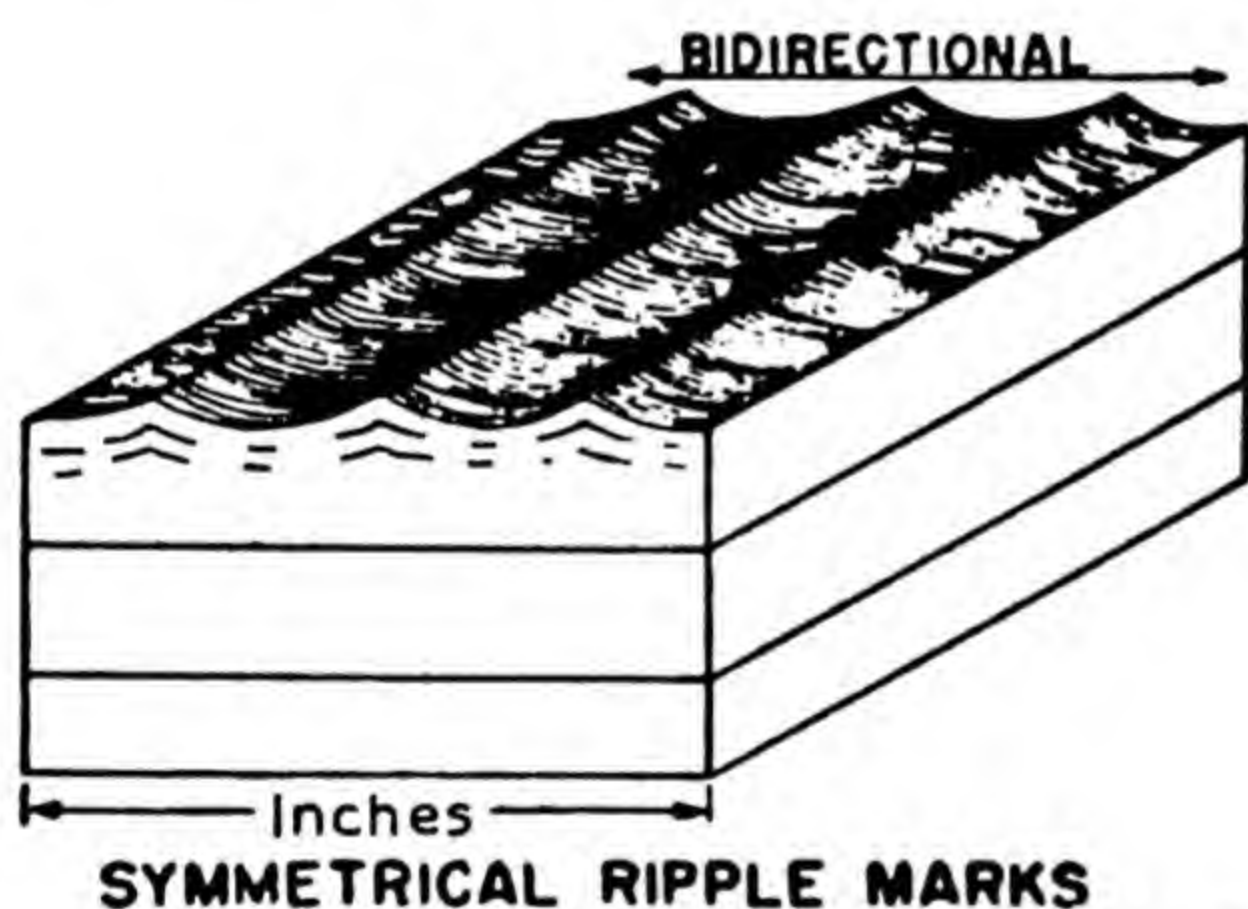
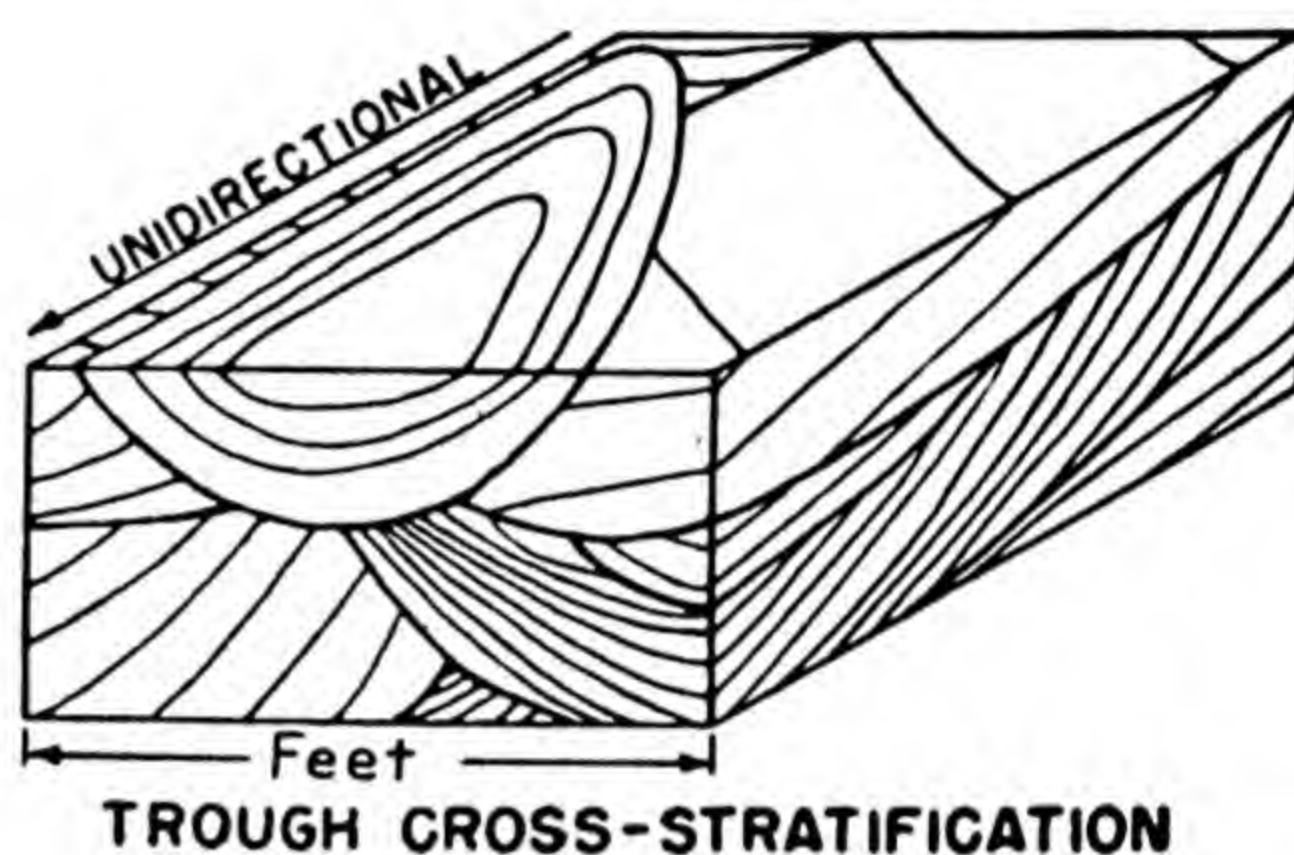
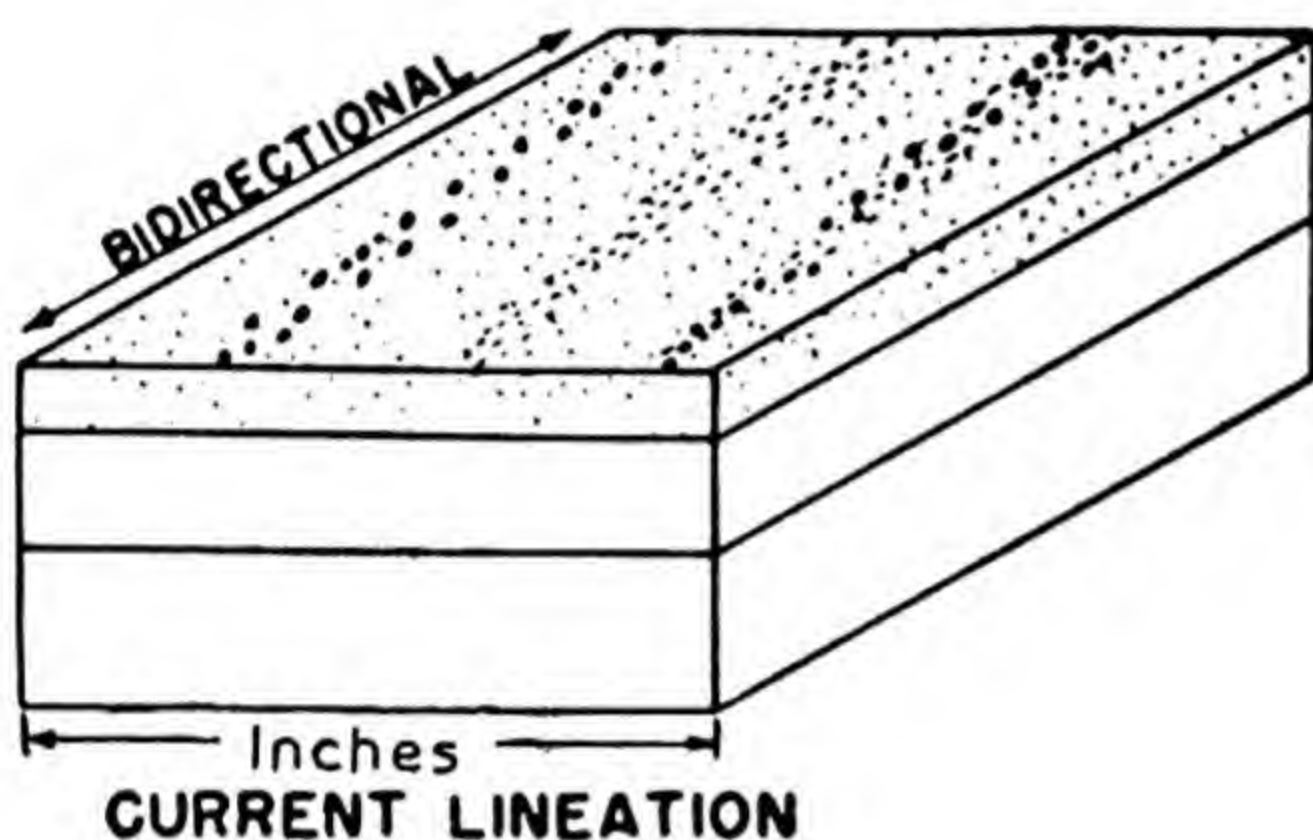
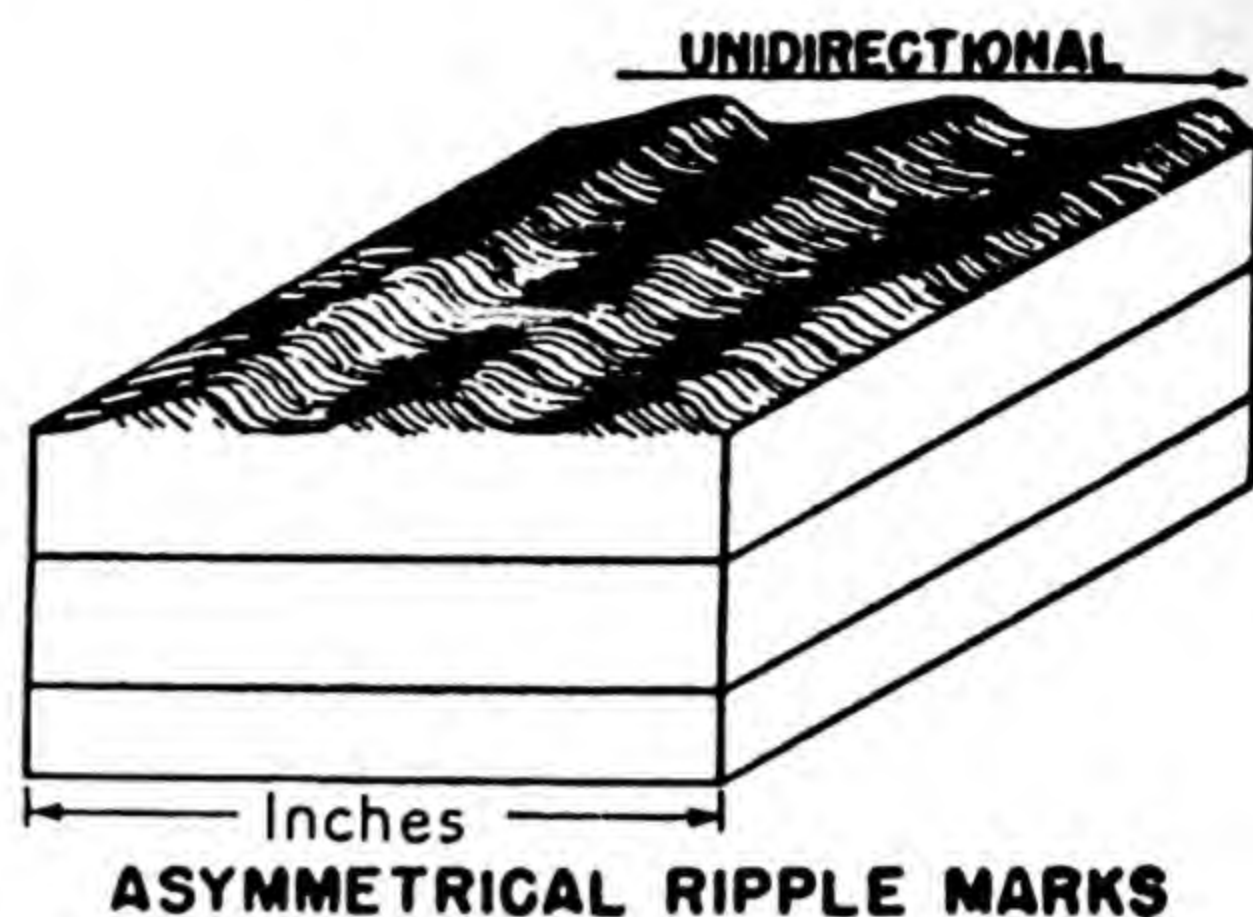
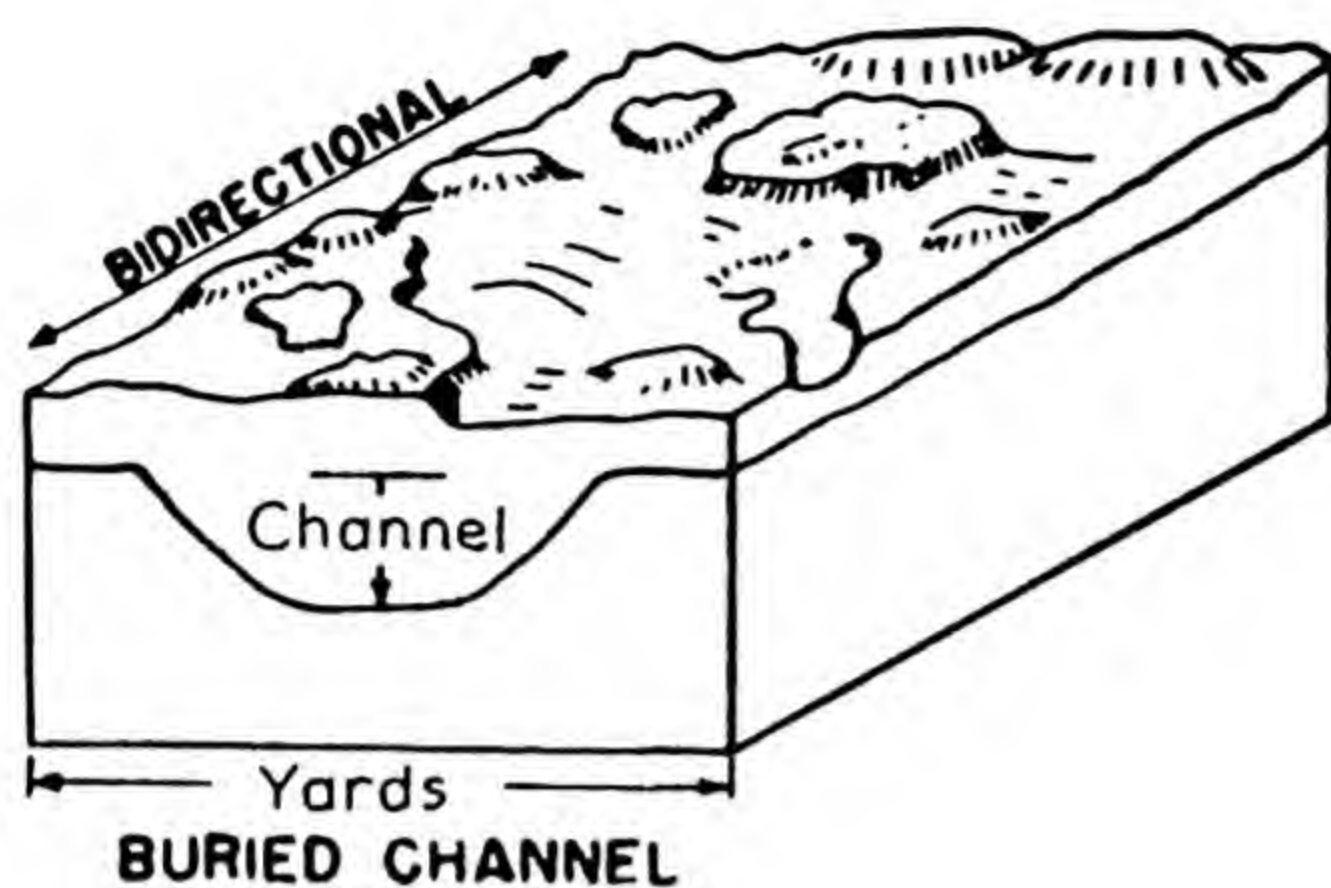
Sedimentary structures (Figs. 1.7 and 1.8) within beds which furnish directional data include cross-strata current lineation and ripple marks. In addition the channels themselves in which deposits are frequently located are often elongated in the direction of transportation. Likewise fossil log orientations may be used to supplement other directional data.

The most significant feature indicating the direction of current flow during sedimentary accumulation is cross stratification. The downslope directions of cross strata are assumed to indicate the direction of flow. In a given area the assembly of observable cross-strata attitudes on a map may indicate the flow pattern. Current lineation and ripple marks furnish confirmatory criteria. In some areas the general average of the positions occupied by logs deposited along channels furnishes further directional information.

Channels (Fig. 1.9) play an important role in connection with many uranium deposits which occur in the Shinarump conglomerate of the Upper Triassic. The localization of ore bodies may be attributed to channels, and commercial ore is restricted to channel fill (GC 39).

Channels represent old stream scours which followed a sinuous course across a slightly tilted or almost flat flood plain. The troughs cut by the streams were





*After Poole and Williams, 1955*

*After Poole and Williams, 1955*

FIG. 1.7. Sedimentary structures. Criteria along exposed channels make possible interpreting flow direction in two ways.

FIG. 1.8. Sedimentary structures. Criteria along exposed channels make possible interpreting flow in a single direction.

filled with gravel, sand, and clay. Such features are common sites for uranium accumulation as they now exist buried beneath overlying strata. The channels in the Monument Valley area of northeastern Arizona range in width from 15 to 2300 feet and may be scoured as much as 75 feet into underlying strata (GC 40).

Channels, as they lie buried beneath hundreds or even thousands of feet of overlying strata, constitute a major problem in uranium exploration. Where



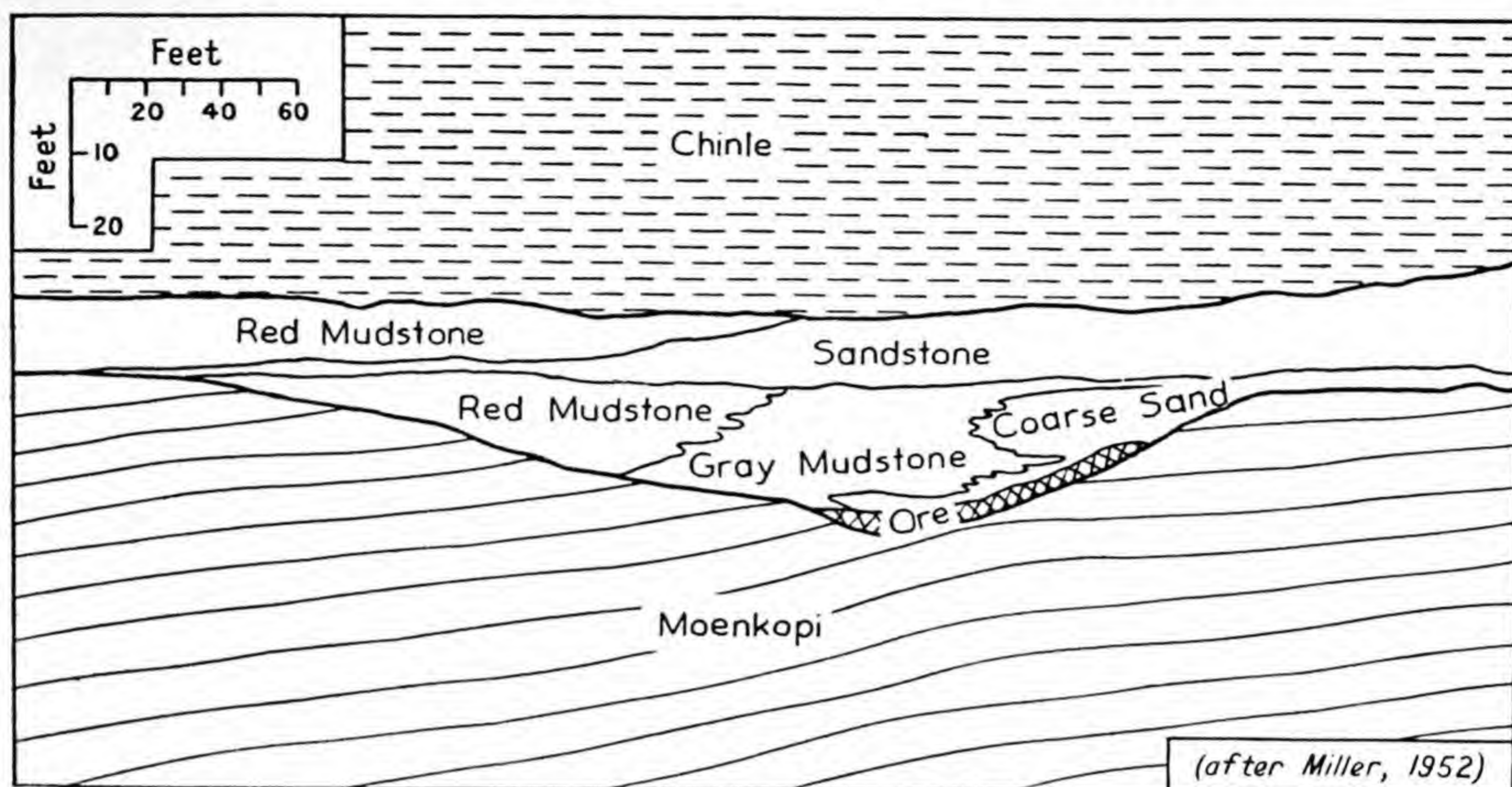


FIG. 1.9. Cross section of ore-bearing Shinarump channel, White Canyon, Utah, U.S.A. The channel has scoured a depression in the underlying formation.

cut by present-day stream courses, cross sections of channels may be recognized on canyon walls. Conglomerate filled troughs, which are frequently gray, contrast in color with the more uniform brown sandstone and shale strata beneath. However, the course of the channel in horizontal extent is usually concealed beneath overlying strata and must be determined by drilling.

**Permeability and fluid transmission.** The permeability of a rock type may be considered as the capacity of the particular rock to transmit fluids under a hydraulic gradient (GC 32). Sedimentary rocks are more permeable parallel to the bedding than across the bedding. In the plane of the bedding they are slightly more permeable parallel to the trend of linear aggregates of sand grains than normal to the aggregates. Other factors being the same, sandstone free from oxidation (which is ordinarily light colored) is somewhat more permeable than oxidized sandstone (which may be dark colored).

The original character of the sediment and subsequent effects resulting in mineral changes influence permeability. In the sediments of the Colorado Plateau the subsequent effects which change the permeability are probably largely minor, and the permeabilities measured represent little change from the original permeability of the rock (GC 33).

Transmissivity represents the capacity of a sedimentary rock as a whole to transmit fluids. The coefficient of transmissivity is equal to the product of the thickness of a bed by its mean permeability (GC 32). Among the rocks of the Colorado Plateau, shales, mudstones, evaporites, and limestones are essentially impermeable and hence are nontransmissive. Transmissive rocks include conglomerates, sandstones, and siltstones.



The transmissive rocks may be divided into two types: (1) eolian sandstones with relatively uniform permeability and thickness, which have largely the same transmissivity over large areas, and (2) fluvial sandstone, siltstone, and conglomerate strata, which vary in thickness and permeability and are highly variable in transmissivity. Most of the known uranium deposits of the Colorado Plateau are characterized by variable transmissivity. It may also be pointed out that the regional transmissive capacity of fluvial sediments as a whole is low relative to eolian sediments (GC 33).

**Precipitants.** Field and laboratory evidence (Miller, 1955) indicates that precipitants play an important role in the deposition of uranium in sedimentary strata.

In the field, organic materials furnish particularly significant associations. Nuclei of plant debris are frequently surrounded by uranium-impregnated sandstone. Accumulations of plant remains in the so-called trash pockets along buried meanders of old stream channels are apt to represent the sites of ore bodies. Logs may be found in which the entire mass has been replaced by pitchblende.

Asphaltic segregations in sandstone may become at times strongly uraniferous. In the core of such masses the asphalt is hard, brittle, and apparently polymerized. Sand grains have been replaced by organic material of petroliferous origin where the uranium mineralization has been most intense. Where both plant debris and petroliferous material have been observed in the same strata, a preference has been noted in which the uranium-bearing solutions replace asphalt and leave the plant remnants largely untouched.

Laboratory study demonstrates that the presence of the  $S^{--}$  ion will bring about the precipitation of pitchblende from solution. The sulfur ion may be present in the form of  $S$ ,  $SO_2$ , or  $H_2S$ . Sulfur is a common associate of organic material in nature, usually in the form of  $H_2S$ ; hence further study will be required to determine the extent to which precipitation in uranium deposits is due to the organic material alone and to the associated sulfur-bearing constituent.

#### URANIUM IN BITUMINOUS STRATA

Uranium may be found under special circumstances in coal, lignite, carbonaceous shale, asphalt, or thucholite. The grade in shale, coal, or lignite is at times low, being measured in grams per ton, but the tonnages involved may be enormous, with deposits underlying many square miles. Shale deposits, stratified, flat-lying or only moderately inclined, and suitably close to the surface to permit large scale mining, have been described in Sweden, the United States, Canada, and Norway. The most widespread are the bituminous shales of Mississippian and Devonian age which underlie large areas of the eastern, central, and mid-western United States and southern Canada. Coal



contains uranium in significant amounts in some areas, although many of the largest and best-known coal areas are comparatively uranium-free. The "kolm" deposits of Sweden (GC 782) and the Great Divide Basin deposits in the western United States (GC 287, 55) furnish examples of areas in which uranium occurs in coal. Lignite apparently may be more uraniferous than coal. Among occurrences in bituminous strata reported to date, the lignite-bearing beds of the South Dakota area in the United States appear to furnish the largest amount of uranium per ton of material mined.

Asphalt at times contains uranium. Fluid accumulations in petroleum reservoirs thought to be associated with asphalt-bearing strata yield the gases helium, radon, and argon and in addition radium and uranium ions in solution, particularly in the brines. Hard, brittle asphaltite (thucholite) has accumulated uranium at localities on the Colorado Plateau where hydrothermal solutions bearing uranium have come into contact with asphalt in granular sediments.

**Mechanism of organic accumulation.** Specific minerals which would account for the uranium in the bituminous shales have not been reported. Uranium ions in the sea water are thought to have been adsorbed by the organic matter at the time the shales were deposited. Shales containing the most uranium may have a high content of phosphate, pyrite, and organic matter mainly as plant debris. Such shales yield oil by destructive distillation and are low in calcium carbonate (GC 51). The role of organic adsorption is supported by experimental observations (GC 49) which show that coal will take up uranium from circulating ground water with the formation of insoluble uranyl humates.

Three mechanisms (GC 49) are recognized by which uranium may become fixed in carbonaceous materials: (1) organic material may serve as a reducing agent to convert the soluble uranyl ion ( $\text{UO}_2^{++}$ ) to an insoluble uranous form; (2) the sulfide ion ( $\text{S}^{--}$ ) normally present in carbonaceous substances acts as a reducing agent to convert the uranyl ion to the uranous form; (3) the carbonaceous material becomes a chemical precipitant for the uranyl ion.

Stratigraphic studies indicate that the more uraniferous shales known in the United States were deposited in epicontinental seas. The amount of uranium adsorbed by the shale appears to differ somewhat, depending on whether deposition occurred in local marine basins, in geosynclinal areas, along geosynclinal fringe areas, or in epicontinental areas.

While adsorption from sea water provides a tenable source for much of the uranium found in black bituminous shale, it has not been generally accepted for all occurrences in natural organic material. Some lignite beds occur beneath tuff-bearing strata known to contain small amounts of uranium. Elsewhere, tuffs may have been removed by erosion, but did overlie lignite for a considerable length of geologic time. Under such circumstances it has been suggested that circulating waters leached uranium from the tuff during some



portion of geologic history and carried it downward where it came in contact with the lignite and was adsorbed by the organic matter.

In the case of more important high-grade lignite, it has been suggested that a deep-seated distant source should be considered for the origin of the uranium ions. The mechanism of emplacement should also include transportation of the uranium laterally through permeable lithologic units (GC 286).

Uranium may be adsorbed by asphalt under conditions which suggest replacement by hydrothermal solutions. At the same time the widespread distribution of traces of uranium in petroleum points to adsorption of uranium by the organic matter at some early stage in formation (GC 288).

**Bituminous black shales.** Significant amounts of uranium are found in the bituminous alum shales of Sweden. The highest values occur in strata of upper-Cambrian and/or lowermost Ordovician age. In seven provinces the alum shale contains about 100 grams of uranium per metric ton. The quantity present in sufficient amounts to justify mining may be estimated in hundreds of thousands of tons of uranium.

In the United States 200 or more stratigraphic units, ranging in age from pre-Cambrian to Tertiary, are known to contain black shale. The shales of Paleozoic age have received the most study from the standpoint of uranium content. In late Devonian and during early Mississippian times widespread blanket deposits of black shale were accumulated in the eastern and central parts of the United States. The Chattanooga shale and certain equivalents such as the New Albany, Ohio and Woodford formations are representative units. Such shale is about 50 feet thick and in general contains between 0.001 and 0.035 per cent uranium (GC 51).

The Chattanooga shale is believed to have accumulated slowly in shallow water. It is postulated that the surface on which the shale was deposited was largely flat, but with a slight slope and containing occasional elevations. The connections with the ocean may have been remote, but are indicated by marine fossils now found in the shale (GC 52).

Basal black shales of Cretaceous Dakota sandstone yield uranium ores of commercial grade in northwestern New Mexico. The main occurrences lie around the upturned edges of the San Juan Basin. The shale beds are discontinuous lenses which are interfingered with discontinuous paleostream-channel sand lenses. Locally, the shales grade into peats and low-rank coals. There are also lenses of sandstone highly contaminated with wood-derived carbonaceous trash. Deposits of uranium in carbonaceous sandstone, carbonaceous sandstone enclosed by shale, black shales interbedded with sandstones, and black carbonaceous shales are reported from the Zuni and Nacimiento uplifts on the southwestern, southern, and eastern sides of the San Juan Basin (GC 50).

No uranium minerals have been recognized in the shales, and the uranium is



presumably absorbed by the organic matter. Occasionally, beds of pure black carbonaceous shale or peat overlying paleostream channels are mineralized in preference to the sands below. Oxidized yellow uranium minerals are found along rock fractures or joint planes in carbonaceous sandstone. The latter represent a secondary mineralization.

**Coal.** Most coal in the United States is essentially free from uranium. In fact, the major coal fields of the Appalachian and mid-continent regions of the United States contain almost no uranium. In the Rocky Mountain region, however, certain large deposits of coal contain uranium (GC 55).

An area of about 750 square miles of the Great Divide Basin, of Sweetwater County, Wyoming, is underlain by uranium-bearing coal which occurs in strata of early Eocene age. Locally, portions of coal beds may contain as much as 0.016% uranium, but most of the coal contains less than 0.003%. Uranium in ash obtained by burning the coal ranges from 0.005% to 0.023% (GC 287).

The Wasatch formation of Eocene age contains up to 700 feet of coal-bearing rocks. The coal contains the most uranium where directly overlain by conglomerate, possibly of Miocene age, or where it is adjacent to permeable sandstone beds in the Wasatch formation.

Three possible sources have been suggested for the uranium in the coal: (1) hydrothermal solutions rising along faults, (2) leaching from granite in the region containing traces of uranium, and (3) leaching from overlying tuffaceous rocks containing traces of uranium. It has been shown by laboratory experiments that the coal could serve as an adsorbent for uranium from natural waters. Petrographic studies show that uranium in the carbonaceous rocks is consistently accompanied by traces of gallium, germanium, iron, molybdenum, lead, vanadium, and the rare earths (GC 56).

**Lignite.** Uranium-bearing lignite deposits are found near the junction of Montana with North and South Dakota about 100 miles north of the Black Hills. Scattered areas of badlands or buttes rise above the rolling prairie. More prominent buttes are underlain by lignite.

Mineralized lignite beds occur throughout 2000 feet of fluviatile deposits of Paleocene and late Cretaceous age. In general, strata are almost flat, being inclined at about 10 to 40 feet per mile northeasterly into the Williston Basin. The uranium content of the organic strata is 0.005% to 0.02%, while the ash yields 0.05% to 0.1%. Almost one-fifth of the uranium-bearing lignite is in beds 4 feet thick and close enough to the surface to permit strip mining. Large tonnages containing an average of 0.008% uranium are available.

High-grade uranium-bearing lignitic material occurs in the northwest corner of South Dakota \* in the Ludlow and Tongue River members of the Fort Union formation of Paleocene age. The lignite is found within 100 feet stratigraphically both above and below the plane of contact between the two members.

\* Also in adjacent North Dakota and Montana. [Ed.]



Mildly radioactive tuffs and bentonites of Oligocene and Miocene age some 250 feet thick overlap the lignites. Chemical analyses of water from the tuff are reported to show significant concentrations of uranium, arsenic, vanadium, molybdenum, and copper. Molybdenum is closely associated with uranium in the lignite in concentrations which range from 0.01% to 1.0% in the residue from burning.

These factors have led to the suggestion that the uranium now found in the lignite was originally a constituent of the volcanic tuff or bentonite. The uranium ions were leached from the tuff strata by percolating waters. The lignitic strata acted as receptors that extracted the uranium by ion exchange or by the formation of organometallic compounds (GC 57).

Several points of evidence favoring the tuff-leach theory of origin as applied to the weakly uraniferous lignite are less conclusive when applied to the high-grade deposits. The beds of high-grade lignite appear to differ from the low-grade in chemical and physical characteristics. The high-grade beds are also localized relative to paleogroundwater systems and are not confined to the stratigraphically or topographically highest lignite. The association of molybdenum with the lignite is considered by King to be incompatible with an origin in sedimentary rocks (GC 286).

**Asphalt.** Spectrographic analyses have been made of asphaltic materials from 49 areas in California, Utah, Wyoming, Montana, New Mexico, Texas, Oklahoma, and Missouri. The asphalt was extracted from the host rock and calcined. The ash was analyzed chemically for uranium and also semiquantitatively for other elements by spectrographic methods. Significant amounts of uranium were found in the ash of the extracted oil the maximum amounts being recorded in Table 1.3.

TABLE 1.3

<i>Source</i>	<i>U%</i>	<i>Source</i>	<i>U%</i>
California		Utah	
Chalone Creek.....	0.50	Vernal.....	0.15
McKittrick.....	0.15	Oklahoma	
Edna.....	1.9	Sulphur.....	0.22
Los Alamos.....	0.33	Missouri	
		Ellis.....	0.41

The average uranium content of the ash for the seven areas ranges from 0.028% to 0.376%. With the exception of Chalone Creek, the areas contain large reserves of asphalt-bearing rock ranging from 15,000,000 to 2,000,000,000 short tons. In thirteen additional areas the average uranium content ranges from 0.02% to 0.068% uranium in the ash of the extracted oil (GC 288).

Host rocks in which the asphalt is found include sandstone, arkose, tuff, limestone, diatomite, and alluvium. It has been shown by chemical analyses that the uranium is concentrated as an organo-uranium complex in the asphalt and



not in the host rock. Apparently the uranium occurred as an original constituent of the oil or was introduced during the migration of the oil.

Crude oils, oil seeps, and petroliferous rocks from the central and western United States have been analyzed for uranium and traces of various metals. Seep oil and other surface accumulations are shown to be generally enriched in uranium in contrast to the crude oil fraction as produced at the wellhead.

The oil-gas reservoirs of the Wichita-Amarillo uplift of Oklahoma and Texas contain concentrations of uranium in the form of metalliferous asphaltite, a carbonaceous mineraloid similar to thucholite, carburan, and huminite. Abnormal concentrations of radon and helium in the Panhandle Field of Texas are associated with uraniferous asphaltite nodules and impregnations. Uraninite, coffinite, and thorite have been reported from nodules; but in many, the uranium-bearing compound (possibly a metallo-organic complex) has not been identified. The trace metal suite corresponds to that found in the ash of crude oil.

The gases radon, helium, and argon, as well as radium, uranium, and thorium, occur in certain oil and gas fields in the United States. The uranium content of oil-field brines subjected to analysis has been found to be as much as 0.2 ppm. Brines also have a high content of radium and yield radium precipitates on pipes.

The genetic relations involved in the origin of helium and the associated uraniferous asphaltites are not too well understood. Evidence to date indicates that asphaltite must have been localized in rock pores in the presence of petroleum or a combination of petroleum and water. The localization also resulted in the concentration of uranium with other metals in disseminated point-segregates. The process of localization was apparently not dependent on the rock type and was effective over broad structural areas.

#### URANIUM IN PHOSPHATE ROCK

Two large areas in the United States have been studied to determine the extent to which uranium might be available as a by-product in mining phosphate rock. Marine phosphorites are widely distributed and contain small amounts of uranium which may be partly recoverable under favorable conditions (GC 290).

Phosphate deposits are found in the Phosphoria formation (Permian) in Montana, Idaho, Utah, and Wyoming over an area of 135,000 square miles (GC 291). In Florida the Bone Valley formation (Pliocene) yields phosphate rock in an area in excess of 1000 square miles, mostly in Hillsborough and Polk counties. The uranium is believed to have been absorbed from sea water by the phosphate particles as they accumulated on the sea floor (GC 293).

The calcium phosphate zone in the lower part of the Bone Valley formation



of Florida and the upper part of the Hawthorne formation on which the Bone Valley rests contains about equal parts of quartz sand, phosphate particles, and slime. A leached zone six to seven feet thick exists at the top of the Bone Valley formation which has been altered by weathering and ground-water action. Here the carbonate-fluorapatite which prevails below the leached zone has been progressively altered to aluminum phosphate. At the same time the uranium content, which is about 0.008% in the lower unaltered rock, is increased to 0.012% (GC 292).

The phosphate content below the leached zone is about 15%  $P_2O_5$ , and within the leached zone it is about 8% to 10%. The weathering has resulted in adding phosphate to the clay constituent and alumina to the apatite. Carbonate-fluorapatite of the unweathered rock below is incipiently leached and altered at the base of the weathered zone. Above in a middle zone the calcium-aluminum phosphates crandallite and millisite are found. At the top the aluminum phosphate, wavellite predominates (GC 292).

#### THORIUM-BEARING DETRITAL DEPOSITS

The most important accumulations of thorium have been formed by mechanical processes in the course of which thorium minerals have been eroded from older rocks, transported by stream action, and deposited in poorly consolidated sediments. Ordinarily, commercial deposits of this type are geologically youthful, and the deposits are loosely compacted. In contrast, pre-Cambrian quartzites, grits, and conglomerates have been found in which thorium has also accumulated by mechanical action. These old rock types are hard, brittle, and compact and often have been recrystallized.

It is interesting to note that no important sources of thorium minerals other than of detrital origin have yet been found in sedimentary rocks of an arenaceous type (GC 301).

More recent loosely consolidated detrital deposits of thorium have been reported in India, Brazil, Taiwan, and the United States. It is stated (GC 875) that the littoral of Travancore-Cochin in India contains over a million tons of monazite, a thorium asset of world importance. Thorium is a constant constituent of Indian monazite to the extent of 8% to 10.5%  $ThO_2$ . Indian monazite is also reported to contain fourteen rare earths and metals of the cerium group. The beach sands of the Malabar and Coromandel coasts furnish the main source of Indian monazite. Both coasts have yielded a number of new deposits during the last two years.

Although each deposit has certain peculiarities, the monazite-bearing concentrations are usually black because of the presence of magnetite and ilmenite, or red where garnet is a noteworthy constituent. In general, the primary source of the monazite (Bain, 1950) is the crystalline rock which lies between the



projected base of the Deccan lavas and the present land surface. The heavy minerals are brought to the coast by streams to form alluvial deposits which in turn are concentrated by along-shore currents.

In the United States, placer deposits containing thorium-bearing minerals and large enough to justify dredging operations occur in Idaho in the Bear Valley area of Valley County. The heavy mineral content of the placers has been determined in pounds per cubic yard as follows:

Euxenite.....	1.0	Zircon.....	0.05	Ilmenite.....	20.0
Monazite.....	0.5	Garnet.....	10.0	Magnetite.....	5.0
Columbite.....	0.2				

Euxenite, a complex rare-earth-uranium-thorium-titanite-columbate, and monazite are the two thorium-bearing minerals in the heavy mineral concentrate (GC 305).

In the Hailey area of Blaine County, Idaho, not far distant from the first area, placers with a considerably different heavy mineral content occur. Here the heavy mineral content in pounds per cubic yard is as follows.

Uranothorite.....	0.5	Zircon.....	0.5	Garnet.....	0.1
		Sphene.....	1.0	Magnetite.....	10.0

The thorium minerals of the placer deposits were apparently derived from quartz-monzonitic phases of the Idaho batholith, one of the great intrusive areas of the western United States. Euxenite, uranothorite, and monazite occur as accessory minerals in the quartz-monzonite. Segregations of these minerals measure from a few inches to tens of feet in diameter. These may contain as much as 0.05 pounds of euxenite per ton at Bear Valley, 0.8 pounds of uranothorite per ton near Hailey, and 0.25 pounds of monazite per ton in the vicinity of Cascade.

Sediments of the Atlantic Coastal Plain yield thorium. Monazite is sparsely but widely distributed as a detrital mineral in Cretaceous, Tertiary, and Quaternary strata. Ordinarily, monazite constitutes less than 0.1% of the sediment.

In the United States, monazite (7.5% Th) occurs in pre-Cambrian quartzite in part of the Marquette iron district in northern Michigan. The thorium mineralization is found in the Palmer area on the south limb of the Marquette synclinalorium in the Goodrich quartzite of upper Huronian age. Monazite occurs in rounded to subrounded grains believed to be of detrital origin. These are concentrated mainly in the matrix of quartz pebble conglomerate which is interbedded with coarse-grained quartzite. Drill-core specimens contain up to 54 pounds of monazite per ton, while samples from glacial erratics and mine dumps contain as much as 110 pounds per ton. When ground to 150 mesh, the monazite is more than 85% recoverable by gravity separation. In view of the



large tonnage of the monazite-bearing quartzite available, the northern Michigan area may represent a considerable potential low-grade monazite reserve.

### INTERPRETATIONS OF ORIGIN

Original sources to which uranium and thorium are attributed in the formation of deposits are (1) molten magma, (2) hot fluids, (3) ground water, (4) surface solutions, (5) sea water, (6) volcanic ash deposits, and (7) deposits exposed to erosion.

**Molten magma.** Direct crystallization of thorium and some uranium occurs in granite and other rock types. Such uranium deposits, with the possible exception of Nigeria, are subcommercial. End-stage residuum which forms dikes (pegmatites) and mixed rocks (migmatites) furnishes choice specimens, but usually fails to yield commercial deposits.

**Hot fluids.** Deposits are formed through the action of heated fluids. They constitute the most widely distributed single group and cover a wide range of temperature, pressure, and chemical conditions. Uranium deposits which belong to this group include Radium Hill, Shinkolobwe, Great Bear Lake, Athabaska, Joachimsthal, Marysvale, and many others. Thorium in the crystalline rocks of India, Brazil, and North America is included.

Radium Hill formed under both high pressure and high temperature from solutions which were rich in iron, titanium, rare earths, and uranium. This occurrence probably represents crystallization under the highest pressure-temperature conditions of the major deposits. This origin appears to follow closely the end stage of pegmatitic igneous activity.

Shinkolobwe exhibits an abundance of nickel and cobalt sulfides which were preceded by widespread replacement of dolomite by magnesium carbonate and silicate minerals. Cubic crystals of uraninite, as well as the related monazite veins, suggest high temperature. The deposit appears to represent pressure-temperature conditions which are lower than those of Radium Hill, but higher than those of the Canadian deposits.

The Athabaska veins of Canada are thought to have originated in solutions at temperatures of 250° to 350°C and to have resulted from surges during widely separated time intervals. Other pitchblende veins of the Canadian Shield may be more or less similar. Precipitation probably occurred deep in the earth's crust.

At Joachimsthal, the prevalence of bismuth and silver may indicate lower temperature conditions than those which prevailed in general on the Canadian Shield. However, the pitchblende is rather similar, and much silver was reported during the early development of Great Bear Lake; the two occurrences, therefore, may be nearly parallel.



At Marysvale, Utah, pitchblende is poorly crystallized and intimately associated with fluorite and pyrite. Clay mineral alteration of the wall rock is intense, although in general, base metal sulfides are absent. That temperatures and pressures were lower is shown by the geological environment.

Where pitchblende deposits occupy vertical or steeply inclined fractures, there is ordinarily agreement that deposition took place from heated solutions. When it occurs in flat or moderately inclined strata, opinions as to origin often differ. This situation particularly applies to deposits of the Blind River–Witwatersrand and the Colorado Plateau types.

A major problem of the Colorado Plateau is the source of the uranium-bearing solutions. Thermal solutions, ordinary ground water, and percolating waters which leach from above have been suggested. Leaching would derive uranium from the ash beds which are abundantly distributed through the plateau strata. Ordinary ground water would find the uranium in pre-existing deposits. Thermal solutions would transport the uranium ions through crustal rocks which exist below the sediments and represent the last phase of igneous activity.

Many difficulties arise in the interpretation of the origin of stratified ore bodies. Ores accumulate in channels, although evidence of the vertical movement of solutions is observed only occasionally, and deposits terminate abruptly above and below. Laboratory evidence indicates that in time pitchblende may be precipitated at temperatures as low as 50°C.

Veins at Los Ochos and Placerville on the Colorado Plateau cut across plateau sediments, yet correspond in mineralization to plateau-type ore bodies. A wide vertical distribution of ore-bearing strata in many formations exists. Upward migration of magnesium and calcium as an accompaniment to ore-bearing solutions has been observed at Temple Mountain. Broadly distributed faults and fractures adequate for the vertical migration of solutions have been recognized. Igneous activity occurs both around and within the plateau in numerous places. In age the pitchblende appears to be younger than the enclosing strata, which indicates later emplacement. Many elements which accompany pitchblende emplacement are uncommon constituents of the accompanying sediments. A number of these elements form minerals which, if found in vein deposits, would be assumed to have been derived from below. Hard, brittle petroliferous materials which contain enough uranium to form ore apparently have been polymerized as a result of abnormal heating. That the oxidized minerals of the plateau strata were not the first to form is indicated by remnant masses of pitchblende and coffinite. Microscopic study and field observation indicate precipitation from solution. Such factors would point to an origin from heated solutions.

The emplacement of uranium in ancient sediments of the Blind River–Witwatersrand type has been subject to two interpretations. In one, the ore was



transported from an ancient source and deposited as the sediments accumulated. In the other, deposition occurred from heated solutions. These ores lie along channels, and their boundaries are reasonably sharp both above and below. The major features of the deposits are sedimentary, although the theory of mechanical transportation and emplacement encounters source difficulty due chiefly to the character of the mineralization. Close study of the minerals indicates that the uranium must have been introduced after the sediments were deposited and probably prior to the cementation which reduced permeability. Here again the weight of evidence appears to favor thermal solutions.

**Ground water.** As heated solutions rise they encounter ground water, but the extent to which metal ions originate at depth in hot fluids or are merely transported from place to place by ground water remains to be determined. Major deposits where the origin of the ions may be traced to hot crustal fluids are well known. The deposition of radium-bearing material out of equilibrium has been observed in ground water around oil fields, although uranium production from such an origin is not reported. If ground water is important as a major originating agent, it should receive much more careful study than it has received in connection with the origin of uranium and thorium.

**Surface solutions.** Uranium is subject particularly to the oxidizing action of surface and near-surface waters, and the end products of this process are oxidized uranium minerals. Deep weathering of pitchblende occurs in permeable areas which are subject to a fluctuating water table as at Rum Jungle, Shinkolobwe, and Gunnar. Wide distribution of uranium by this method is doubtful.

**Sea water.** The theory of widespread distribution of small amounts of uranium in organic shales and phosphate rock by adsorption from sea water during accumulation appears to be widely accepted. Yet the uniformity of such distribution indicates that other conditions must be considered in order to account for local concentrations of ore in areas such as South Dakota.

**Volcanic ash deposits.** In the Wyoming-South Dakota area, some authors devote particular attention to uranium concentrations in sedimentary strata as being due to the leaching of overlying ash deposits by surface waters. However, others who have worked in the area assign the origin to rising thermal waters. Although the literature provides important items in support of both hypotheses, until more information is available on the uranium content of volcanic ash and the distribution of uranium in strata both above and below known deposits, the origin may not be explained properly.

**Deposits exposed to erosion.** Thorium-bearing placers of India, Brazil, and Idaho are derived from the mechanical destruction of pre-existing thorium-bearing rocks. Although thorium minerals have resistant properties which permit widespread transportation prior to accumulation in detrital deposits, ura-



niun minerals disintegrate in this process. However, uranium may be found in minor amounts with thorium.

# SELECTED REFERENCES FOR CHAPTER 1

- Bain, G. W., 1950: Geology of the fissionable materials. *Econ. Geol.* 25:273-323.
- Bannister, F. A., and J. E. T. Horne, 1950: A radioactive mineral from Mozambique related to davidite. *Min. Mag.* 29:101-112.
- Barth, T. F. W., 1951: *Theoretical Petrology*. New York, John Wiley & Sons, Inc., 387 pp.
- Buttenbach, H., 1925: *Minéralogie du Congo Belge*. Brussels, M. Hayez, 183 pp.
- Cohen, W. J., 1953: A note on pitchblende and uraninite. *Annual Report for June 30, 1952 to April 1, 1953*, U.S. Atomic Energy Commission, RME-3046, pp. 58-63.
- Collins, C. B., R. M. Farquar, and R. D. Russell, 1954: In H. Faul (Ed.), *Nuclear Geology*. New York, John Wiley & Sons, Inc., p. 270.
- Davidson, C. F., 1953: The gold-uranium ores of the Witwatersrand. *Min. Mag.* 88:73-85.
- Davidson, C. F., and J. A. E. Bennett, 1950: The uranium deposits of the Tete district, Mozambique. *Min. Mag.* 29:291-303.
- Davidson, C. F., and S. H. U. Bowie, 1951: On thucholite and related hydrocarbon-uraninite complexes. *Bull. Geol. Surv. Gt. Britain*, No. 3, pp. 1-19.
- Ellsworth, H. V., 1928: Thucholite, a remarkable primary carbon mineral from the vicinity of Parry Sound, Ontario. *Am. Min.* 13:419-441.
- 1932: Rare-element minerals of Canada. Canada Dept. Mines, *Econ. Geol. Series*, No. 11, p. 242.
- Everhart, D. L., and R. J. Wright, 1953: The geologic character of typical pitchblende veins. *Econ. Geol.* 48:77-96.
- Faul, H. (Ed.), 1954: *Nuclear Geology: A Symposium on Nuclear Phenomena in the Earth Sciences*. New York, John Wiley & Sons, Inc., 414 pp.
- Fischer, R. P., 1950: Uranium-bearing sandstone deposits of the Colorado Plateau. *Econ. Geol.* 45:1-11.
- Fisher, N. H., and C. J. Sullivan, 1954: Uranium exploration by the bureau of mineral resources, geology and geophysics, in the Rum Jungle province, northern territory, Australia. *Econ. Geol.* 49:826-836.
- Fleischer, M., 1953: *Recent Estimates of the Abundance of the Elements in the Earth's Crust*. U.S. Geol. Survey, Circular 285, 7 pp.
- Fraser, J. A., 1954: *Crackingstone, Saskatchewan*. Dept. Mines and Tech. Surveys, Geol. Survey of Canada, Paper 54-8, 1 map.
- Fraser, J. A., and S. C. Robinson, 1954: Preliminary description of the geology and mineralogy of the Gunnar deposit, Saskatchewan. *Canadian Mining Journal* 75:59-62.
- George, D'Arcy, 1949: *Mineralogy of Uranium and Thorium Bearing Minerals*. U.S. Atomic Energy Commission, RMO-563, 198 pp.
- Gruner, J. W., 1954: The uranium mineralogy of the Colorado Plateau and adjacent regions. *Guidebook No. 9*, Utah Geol. Soc., Utah Geol. and Mineral Survey, Salt Lake City, 8 pp.
- Isachsen, Y. W., T. W. Mitcham, and H. B. Wood, 1955: Age and sedimentary environments of uranium host rocks, Colorado Plateau. *Econ. Geol.* 50:127-134.
- James, W. F., A. H. Lang, R. Murphy, and S. N. Kesten, 1950: Canadian deposits of uranium and thorium. *Min. Eng.* 187:239-255.



- Joubin, F. R., 1954: Uranium deposits of the Algoma District, Ontario. *Trans. Can. Inst. Min. Met.* 58:431-437.
- Kerr, P. F., G. P. Brophy, H. M. Dahl, J. Green, and L. E. Wooldard, 1955: Alteration and uranium mineralization, Marysvale, Utah. *Geol. Soc. Am. Memoir* (in press).
- Kerr, P. F., D. R. Kelley, W. S. Keys, and M. W. Bodine, Jr., 1955: Collapse features, Temple Mountain uranium area, Utah. *Annual Report for June 30, 1954 to April 1, 1955*, U.S. Atomic Energy Commission, RME-3110 (Pt. III).
- Kidd, D. F., and M. H. Haycock, 1935: Mineragraphy of the ores of Great Bear Lake. *Geol. Soc. Am. Bull.* 46:879-960.
- Kulp, J. L., G. L. Bate, and B. J. Giletti, 1955: New age determinations by the lead method. *Geol. Assoc. Canada Proceed.* 7(2):15-24.
- Lang, A. H., 1951: *Canadian Deposits of Uranium and Thorium*. Geological Survey of Canada, Paper 51-10, 157 p.
- 1952: *Canadian Deposits of Uranium and Thorium (Interim Account)*. Geological Survey of Canada, Econ. Geol. Ser. No. 16, 173 p.
- 1952: Uranium orebodies. *Canadian Min. Jour.* 73:57-65.
- Larsen, E. S., Jr., and G. Phair, 1954: The distribution of uranium and thorium in igneous rocks. In H. Faul (Ed.), *Nuclear Geology*. New York, John Wiley & Sons, Inc., pp. 75-89.
- Lovering, T. G., 1955: Progress in radioactive iron oxides investigations. *Econ. Geol.* 50:186-195.
- Lowell, J. D., 1955: Applications of cross-stratification studies to problems of uranium exploration, Chuska Mountains, Arizona. *Econ. Geol.* 50:177-185.
- Miller, L. J., 1955: Uranium ore controls of the Happy Jack deposit, White Canyon, San Juan County, Utah. *Econ. Geol.* 50: 156-169.
- Nier, A. O., 1939: Isotopic constitution of radiogenic leads and the measurement of geological time. *Phys. Rev.* 55:153-163.
- Nininger, R. D., 1954: *Minerals for Atomic Energy*. New York, D. Van Nostrand Company, Inc., 367 pp.
- Page, L. R., 1950: *Interim Report of Geologic Investigation, Lost Creek Schroeckingerite Deposits, Sweetwater County, Wyoming*. U.S. Geol. Survey, TEM-183-A, pp. 1-3.
- 1950: Uranium in pegmatites. *Econ. Geol.* 45:12-34.
- Parkin, L. W., and K. R. Glasson, 1954: The geology of the Radium Hill uranium mine, South Australia. *Econ. Geol.* 49:815-825.
- Rankama, K., and Th. G. Sahama, 1950: *Geochemistry*. Chicago, University of Chicago Press, 912 pp.
- Rasor, C. A., 1952: Uraninite from the Grey Dawn mine, San Juan County, Utah. *Science* 116:89-90.
- Robinson, S. C., 1955: *Mineralogy of Uranium Deposits, Goldfields, Saskatchewan*. Geological Survey of Canada, Bull. 31, 128 p.
- Rosenzweig, A., J. W. Gruner, and L. Gardner, 1954: Widespread occurrence and character of uraninite from the Triassic and Jurassic sediments of the Colorado Plateau. *Econ. Geol.* 49:351-361.
- Rowe, R. B., 1954: *Notes on Geology and Mineralogy of the Newman Columbium-Uranium Deposit, Lake Nipissing, Ontario*. Geological Survey of Canada, Paper 54-5, pp. 1-25.
- Satterly, J., and D. F. Hewitt, 1955: *Some Radioactive Mineral Occurrences in the Bancroft Area*. Ontario Dept. Mines, Geol. Cir. No. 2, pp. 1-62.
- Stieff, L. R., T. W. Stern, and A. M. Sherwood, 1955: Preliminary description of coffinite—a new uranium mineral. *Science* 121:608-609.



- Traill, R. J., 1954: A preliminary account of the mineralogy of radioactive conglomerates in the Blind River region, Ontario. *Can. Min. Jour.* 75: 63-67.
- Urey, H. C., 1952: *The Planets, Their Origin and Development*. New Haven, Yale University Press, 245 pp.
- Weeks, A. D., and M. E. Thompson, 1954: *Identification and Occurrence of Uranium and Vanadium Minerals from the Colorado Plateaus*. U.S. Geological Survey, Bull. 1009-B, 62 pp.
- Wright, R. J., 1955: Ore controls in sandstone uranium deposits of the Colorado Plateau. *Econ. Geol.* 50:135-155.
- Wyant, D. G., 1952: *Lost Creek (Wamsutter) Schroeckingerite Deposit, Sweetwater County, Wyoming*. U.S. Geological Survey, TEM-10-B, pp. 1-9.



## *Chapter 2*

---

### THE NATURAL OCCURRENCE OF URANIUM IN THE UNITED STATES \*

---

---

Uranium has been found in all major geologic environments in the United States except those typified by ultramafic and plateau basalt igneous rocks, and except certain marine sediments.

Concentrations of uranium occur in igneous rocks, veins, terrestrial clastic rocks; precipitates and evaporites; lignites, coal, and asphaltic materials; marine black shales and phosphorites. Most of the uranium deposits of ore grade are in the orogenic belt between the 100th and 120th meridian of west longitude; a few occur elsewhere.

Some igneous rocks contain much more uranium than do most granites. The uranium occurs as discrete uranium minerals, disposed in the structure of the rock-forming minerals, adsorbed on surfaces of grains, and dissolved in fluid inclusions and intergranular fluids. The uraniferous intergranular fluids are leachable in dilute acid and may offer a very low-grade, exploitable source of uranium for the future.

Uraniferous vein deposits in western United States are mainly Tertiary in age, and most of the exploitable deposits are in crystalline rocks of pre-Cambrian, Mesozoic, and Tertiary age. Occurrences in eastern United States, mostly undated, are mainly in rocks of Paleozoic or pre-Cambrian age. Pitchblende or uraninite, associated with base metal sulfides or with fluorite, are the principal uranium minerals in the vein deposits at depth. Supergene secondary uranium minerals occur in some deposits, but are not abundant.

The vein minerals for the most part were deposited under near-surface conditions; a few may have been formed at intermediate depths. Hydrothermal alteration of the wall rocks includes silicification, sericitization, chloritization, argillization, and alunitization. Red hematite zones adjacent to veins are very common.

\* Oral summary of Geneva Conference Paper 471, "Natural Occurrence of Uranium in the United States" by staffs of the U.S. Geological Survey and the U.S. Atomic Energy



The principal source of uranium in the United States, however, is terrestrial sandstones, mudstones, and limestones, in which the uranium minerals occur disseminated as pore fillings and impregnations. The largest and most numerous of these deposits are in rocks of Mesozoic age on the Colorado Plateau, but similar deposits also occur in Mesozoic and Tertiary rocks on the fringes of the Plateau, and in the Cordilleran Foreland east of the main folded and thrust belts of the Rocky Mountains. Uranium also occurs in Paleozoic sandstones on the Colorado Plateau, and in Texas, New Mexico, Oklahoma, and Pennsylvania. In all, 37 sedimentary units have yielded uranium; 18 have furnished at least 1000 tons of ore averaging more than 0.1%  $U_3O_8$ .

The favorable areas are characterized by simple folded mountains alternating with broad, asymmetric basins. In the Black Hills of South Dakota and Wyoming the uraniferous districts are above major structural terraces on the pre-Cambrian surface, and the individual deposits are on similar minor structures in Cretaceous sandstones. Likewise in the Colorado Plateau, regional structures such as uplifts, faults, joints, and tertiary igneous stocks and laccoliths appear to influence the distribution of ore deposits, although sedimentary structures are the dominant local control.

Chemical, mineralogic, and geologic evidence indicates that the well-known carnotite ores have been derived by progressive oxidation of primary black vanadium-uranium ores. The primary ores contain uranium in uraninite and coffinite  $[U(SiO_4)_{1-x}(OH)_{4-x}]$  and vanadium in montroseite and roscoelite. Minor amounts of copper, iron, lead, and zinc sulfides are common; arsenides and selenides are less common. Most uraninite and coffinite replace or impregnate coalified wood or other carbonaceous material. On oxidation, montroseite alters to paramontroseite and another unknown vanadium oxide, then to corvusite group minerals. The primary uranium minerals oxidize and combine with vanadium to form rauvite  $[CaO \cdot 2UO_3 \cdot 5V_2O_5 \cdot 16H_2O]$  and with further oxidation, carnotite, and tyuyamunite.

The nonvanadiferous primary ores contain more abundant copper sulfides with uraninite and on oxidation yield a wide variety of secondary hydrated oxides, carbonates, sulfates, phosphates, arsenates, and silicates.

On the Colorado Plateau the most significant production is obtained from formations containing varying proportions of fluvial conglomerates, sandstones, and mudstones in which plant debris is abundant. Copper, copper-uranium, and vanadium-uranium deposits, both oxidized and unoxidized, have been found; uraninite is the chief ore mineral in many deposits. Exploitable ores in many places are restricted to the sides and bottoms of channel fillings in shallow depressions in the lower contact of the porous clastic rocks. In other places they are not restricted to channels or to any particular stratigraphic unit;

Commission, Division of Raw Materials. Presented by Lincoln R. Page, U.S. Geological Survey, Washington, D. C.



most, however, are in sandstones or coarse clastics in the lower part of the formation.

They may be localized in the thicker parts of the sandstone lenses by sedimentary structures, such as channels, lenses, and intersections of crossbeds, and have their long axes parallel to current lineation, festoon bedding trends, and scours.

Green or gray alteration zones are common around deposits, particularly in the red mudstones below the ore-bearing clastic rocks, and their thickness can be correlated with the presence of deposits in many places.

Large ore deposits of the Plateau type occur in the lacustrine Todilto limestone of Jurassic age in New Mexico and appear to be confined to intraformational, anticlinal folds in the troughs of shallow synclines. The ore bodies are long and narrow; the trends follow the reticulate joint and fold pattern.

Very recently, significant ore deposits have been found in lignites of Paleocene age in northwestern South Dakota and adjacent parts of North Dakota and Montana. Isolated samples of the lignite in these deposits contain as much as 10% uranium. Carnotite, autunite, torbernite, metazeunerite, and coffinite have been identified and are believed by many geologists to have resulted from leaching of overlying tuffaceous rocks.

Widespread uraniferous marine sedimentary rocks include the phosphatic rocks of Permian age in Idaho, Montana, Wyoming, and Utah and of Tertiary age in Florida; the Chattanooga black shale of Devonian and Mississippian age; and some black shales of Pennsylvanian age in the Central States. The uranium content generally is less than 0.01%. Aluminum phosphate deposits of slightly higher grade have been derived from the weathering of marine phosphorites and of phosphatic nodules in some marine black shales. Marine sandstones, conglomerates, mudstones, and limestones rarely contain concentrations of uranium. Because the marine phosphorites are of wide extent, they contain large tonnages of uranium, some of which can be recovered, under favorable conditions, as a by-product of the manufacture of triple superphosphate.

In the United States, as in some other countries, many of the more important deposits are those in which uraninite is disseminated in sedimentary or meta-sedimentary rocks, and vein deposits are playing a less important role. This requires that we review the classical theories of origin of uranium deposits. Studies of the absolute age of uranium minerals have been especially important in this connection, and deposits such as the carnotite of the Colorado Plateau, formerly considered essentially syngenetic, are now known to be clearly epigenetic. This fact, together with the spatial distribution of some deposits, implies that the uraniferous solutions traveled tens of miles along the porous clastic host rocks before deposition took place. Many geological relationships suggest that the uranium was derived from the enclosing rocks by leaching; others suggest that the uranium was derived from juvenile solutions mixing with ground water.



## Chapter 3

---

### THE GENESIS OF URANIUM DEPOSITS \*

---

Concentrations of uranium more than ten times the average of the earth's crust, i.e., more than 0.002% U, are formed by a variety of igneous and sedimentary rock-forming processes as well as by ore-forming processes as they are ordinarily conceived. The nearly ubiquitous geologic distribution of uranium stems, of course, from its chemical and physical properties, particularly its polyvalence, its large atomic radius, its high chemical reactivity, the relative solubility of many of its hexavalent compounds in aqueous solutions, and its relative abundance compared to some other ore metals. These attributes permit it to form compounds with many other elements, to enter the structure of a wide variety of minerals, to take part in many chemical reactions, and hence to be deposited in many rocks and minerals of diverse origins and compositions. The same properties that lead to the wide geologic distribution of uranium also lead to its dispersion so that concentrations of uranium are not as great as those of other, less active metals of comparable abundance, such as lead and molybdenum. The partition of uranium from other elements, and hence its concentration in valuable deposits, seems to be favored by its large radius and high valence, which prevent concentration in ordinary rock-forming minerals, and also by the relative insolubility in aqueous solutions of its common tetravalent compounds, which leads to the precipitation of uranium in a wide variety of environments where reducing conditions prevail.

In the summary that follows attention is focused on the origin of deposits that are currently and potentially most important economically—specifically the uraniferous igneous rocks, the hydrothermal veins, the uranium deposits in sandstones, uraniferous coals and associated carbonaceous shales, uraniferous marine black shales, and uraniferous marine phosphorites. Moreover, we give most consideration to those hypotheses which seem most tenable to us.

\* From Geneva Conference Paper 300, "Summary of Hypotheses of Genesis of Uranium Deposits" by V. E. McKelvey, U.S. Geological Survey, D. L. Everhart, U.S. Atomic Energy Commission, and R. M. Garrels, U.S. Geological Survey.

Selected references for this chapter are listed alphabetically at the end of the chapter.



## URANIFEROUS IGNEOUS ROCKS, PEGMATITES, AND MIGMATITES

The uranium content of igneous rocks is about 0.03 part per million in ultramafic rocks, 1 ppm in gabbroic rocks, 2 ppm in intermediate rocks, and 3 to 4 ppm in granitic rocks and reaches a maximum of 10 to 200 ppm in a few alkalic granites. The unmistakable enrichment of uranium in intrusives rich in silica and alkalis is observable also in volcanics. Some silica-poor rocks, such as lamprophyres, are also relatively rich in uranium, however; Larsen and Phair believe that "the safest generalization that can be made at this time is that the maximum concentration of uranium and thorium is found in the youngest member of a series, regardless of the particular liquid line of descent that the magma may have followed."

The uranium and thorium fractionation in igneous rocks is explained by Larsen and Phair as a function of the size, valence, and abundance of the uranium ion and of oxidation-reduction equilibria. Because uranium is low in concentration in basic magmas and because the large size and tetravalence of the uranium ion impose hard-to-meet coordination requirements, uranium neither precipitates as a separate mineral nor isomorphously substitutes in plagioclase and other rock-forming minerals. Hence uranium concentrates in late-stage magmas from which it may be deposited as a minor constituent of accessory minerals (such as zircon, xenotime, apatite, and sphene) in which it can substitute isomorphously. As differentiation proceeds toward the highly hydrous pegmatite stage, more uranium is deposited as discrete minerals and less enters the accessory minerals, probably because increase in the water content of the magma reduces the solubility of tetravalent uranium. During very late magmatic stages, uranium may be oxidized to the hexavalent state, possibly as a consequence of pressure changes. This shift to oxidizing conditions is shown by the replacement of early formed ferrous magnesium silicates by magnetite. In the hexavalent state, uranium forms relatively soluble compounds in aqueous solutions. Some may be deposited as acid-soluble, interstitial material from residual solutions but much of the uranium is carried off in hydrothermal solutions. Deposition of uranium in veins takes place when conditions once again become reducing, a conclusion in accord with the facts that the common vein mineral is pitchblende and that sulfides are a constant component of pitchblende veins.

Pegmatites contain a wide variety of uranium minerals, including uraninite as well as many multiple oxides containing rare earths, niobium, tantalum, and titanium. According to Page uranium minerals appear to be commonest in those bodies that contain an abundance of potash feldspar; in zoned pegmatites they are most common in intermediate zones and cores also rich in potash. The covariation of uranium with potash has also been noted in



igneous rocks and is explained as a reflection of the exclusion of these two elements (because of their radie and coordination numbers) from common minerals formed during earlier stages of crystallization. Zonation of pegmatites is now believed to result from fractional crystallization of the pegmatite liquid from the walls inward, so the zonal distribution of uranium in pegmatites also demonstrates its tendency to concentrate in late-stage liquids. Some pegmatites or zones within pegmatites, particularly those that contain uraninite, minor sulfides, and no thorium, are somewhat veinlike in character and may have formed as a result of replacement by or direct deposition from high-temperature hydrothermal solutions.

Certain migmatites in Canada (composed of thin, parallel bands of granite pegmatite) and biotite-bearing schist or gneiss contain uraninite or uranothorite. The origin of migmatites in general is controversial: they may have been formed as a result of partial fusion of sedimentary rocks by injection of granitic material, or by replacement from high-temperature hydrothermal solutions. The origin of the uranium-bearing migmatites has been little studied, but as Adams implies, analysis of their uranium-thorium ratios might show whether they have been derived from primary igneous sources or from partial fusion of sedimentary rocks. In any event, the uranium in migmatites was deposited at high temperatures.

#### URANIUM IN HYDROTHERMAL VEIN AND REPLACEMENT DEPOSITS

Three important types of uraniferous veins may be recognized: (1) nickel-cobalt-native silver veins, (2) silica-iron-lead veins, and (3) iron-titanium veins. The nickel-cobalt-native silver veins are characterized by pitchblende, a complex assemblage of sulfides, carbonates, and minor amounts of silica; they occur typically in metasediments and metavolcanics and are represented by large deposits such as those at Shinkolobwe and Great Bear Lake. The silica-iron-lead veins are also characterized by pitchblende, but the assemblage of associated minerals is generally a simple one, mainly pyrite, galena, and quartz or jasper. They occur mainly in felsic intrusives; examples are deposits at Urgeirica, Portugal, and Marysvale, Utah. The iron-titanium veins are characterized by uranium titanites (such as davidite), ilmenite, rutile, and quartz. They occur mainly in igneous intrusives and are typified by the deposits at Radium Hill, South Australia. Disseminated iron oxides are widespread in all these deposits.

As discussed in the foregoing section, uranium in hydrothermal veins is derived mainly from residual solutions arising from late-stage differentiates, generally those rich in silica and the alkalies. The problems of chief concern, then, are the composition and temperature of transporting solutions, depth and

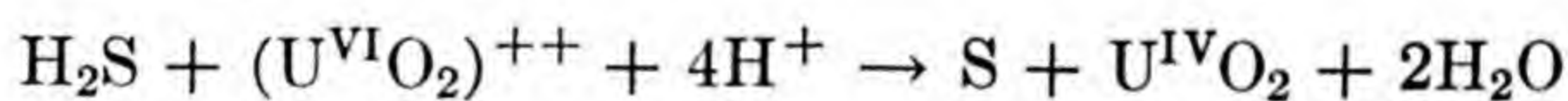


pressure relationships at the site of deposition, the chemistry of precipitation, and structural control in the localization of the ore.

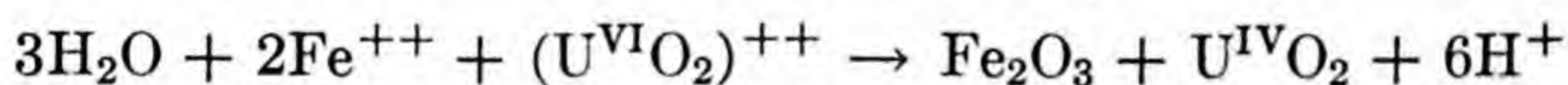
Little is known directly about the composition of uranium-bearing hydrothermal solutions, but from the fact that the most uraniferous natural waters are those high in sulfate and/or carbonate, as well as from experimental data that indicate the solubility of uranyl sulfates and carbonates in aqueous solutions, it may be assumed that uranium is transported as the uranyl ion in sulfate or carbonate solutions and that they may be either acid or alkaline. Because the physical chemical properties of  $\text{CO}_2$  and the system  $\text{CO}_2\text{-H}_2\text{O}$  indicate that under some shallow earth conditions  $\text{CO}_2$  can exist as a separate phase with a density approximately that of water, liquid  $\text{CO}_2$  has also been suggested as the ore-transporting solution.

From the mineral assemblages as well as some experimental evidence, the Si-Fe-Pb veins that contain sooty pitchblende are classed as epithermal; the remainder of the silica-iron-lead veins and the Co-Ni-Ag veins are believed to be mesothermal; and some uraninite, brannerite, and davidite veins which somewhat resemble pegmatite deposits are regarded as hypothermal. The temperature of the transporting fluids and the depth and pressure at the site of deposition of the uranium veins are thus believed to have ranged widely. Field evidence strongly indicates that most of the pitchblende veins were formed at depths shallow enough and at pressures low enough to provide open spaces along regular fissures.

Precipitation of primary uranium minerals in veins may be caused solely by a reduction in the amounts of sulfate or carbonate in solution by whatever cause, by a decrease in temperature, pressure, or both, or by chemical interaction with the host rock. Either pressure or chemical interaction with the host rock may result in uranyl ion reduction, which seems to be the factor of major importance in the precipitation of uranium minerals in hydrothermal and many other types of deposits. Experiments indicate that pitchblende may be precipitated from uranyl sulfate solutions by the use of hydrogen sulfide gas, according to the equation



Ferrous iron may also be a reducing agent for uranyl ion. The reaction



goes to completion (uranyl ion concentration  $<1$  ppm) at  $25^\circ\text{C}$ , pH4 and above, over a wide range of  $\text{Fe}^{++}$  concentration. This may explain the widespread association of iron oxide with pitchblende in vein deposits.

Most of the pitchblende vein deposits show a marked structural control, a tendency to be deposited along straight portions of fractures rather than along crooked portions. In a few deposits pitchblende is found impregnated



in wall rock, but most deposits away from through-going structures are concentrated along related tensional fractures. Replacement deposits are rare except in carbonatic or carbonaceous host rocks and in some high-temperature deposits.

### URANIUM DEPOSITS IN SANDSTONE

The two best-known uraniferous sandstone districts are those of the Colorado Plateau and the Witwatersrand. Unweathered deposits in both districts consist of pore-space fillings of uraninite, pyrite, and other sulfides, generally associated with carbon in the form of woody or asphaltic material. In addition, coffinite (an hydroxy-substituted uranium orthosilicate) and low-valent vanadium minerals are prominent in some of the Plateau deposits; and gold, of course, is an important constituent of the Rand deposits. Individual ore bodies are roughly parallel to bedding, are tabular and generally elongate in shape, and range in size from a few tons to millions of tons. They are best developed in or along the margins of thicker and more permeable zones within the sandstones, such as fossil stream channels. Deposits are widespread within individual, relatively thin zones, but in both the Plateau and Rand districts, deposits are found in many beds over a wide stratigraphic range. The host rocks are nonmarine, generally fluviatile sandstones or conglomerates, though related deposits are occasionally found in rocks of other lithology. Whereas the distribution of the deposits is conspicuously related to sedimentary features, it is less commonly or only inconspicuously related to fractures and igneous rocks. Alteration of host rocks is not pronounced, although red mudstones are bleached to a gray or greenish color in the vicinity of ore deposits on the Plateau, kaolinite is associated with some deposits on the Plateau, and chlorite is prominent in both the Plateau and Rand deposits.

Nearly all who have studied the sandstone deposits interpret the paragenetic relationships of ore and host rock minerals to mean that the ores in their present form were deposited after the enclosing rocks. Many believe, however, that the chief ore metals were introduced during or shortly after deposition of the host rocks, although most of those who favor a placer hypothesis agree that the sulfides were introduced later. New and convincing evidence on this problem with respect to the Plateau ores has been presented recently by Stieff, Stern, and Milkey, who show that the mean  $\text{Pb}^{206}/\text{U}$  age, after correction for the common Pb present, of many samples of Plateau ores is 71 million years, or about half the age of the enclosing rocks. The mean age of samples from ores in the Jurassic Morrison and Entrada formations and the Triassic Shinarump conglomerate are 72, 50, and 73 million years, respectively. These ages are much younger and more uniform than would be expected if the ores were formed at the time of deposition of the host rocks, but they compare favorably to the 60.5 million years determined as the mean



age of four pitchblende samples from hydrothermal veins in the Colorado Front Range. Stieff, Stern, and Milkey interpret their results to mean either that syngenetic uranium deposits were redistributed in late Cretaceous or early Tertiary time or that the uranium was introduced from depth at that time. They regard the first alternative as less probable because in such a redistribution the common lead found in the ores would be transported and redeposited with the uranium and the previously formed radiogenic lead carried away or deposited elsewhere.

Recent age determinations reported on Rand ores by Davidson and by Louw give ages of 1682 and 1850–1950 million years respectively. Davidson, however, has since revised his figure to 465–816 million years. These ages are older than the Witwatersrand system was previously thought to be, but until Louw's determination is better established, the significance of the isotopic data will remain uncertain. Stieff believes correction for old radiogenic lead in the ore may significantly lower the ages computed by Louw. However, the occurrence of low-density thucholite with the gold in the Rand ores—an anomaly hardly explainable if both were placer minerals—supports the conclusion that the uranium in the Rand ores is also epigenetic.

Several sources have been postulated for the uranium in the sandstone ores: (1) detrital uranium minerals or chemical or biochemical precipitates of uranium deposited at the same time as the enclosing rocks, (2) dispersed concentrations in tuffs or ordinary rocks in the sedimentary column, (3) migrating petroleum or solutions derived from petroleum source beds, and (4) hypogene solutions. In our opinion, syngenetic sources may be omitted from further consideration because of the evidence already cited, as well as the facts that uranium on both the Plateau and the Rand occurs in many horizons over a wide stratigraphic range, uraninite is nearly unknown as a placer mineral, and uranium, when it is concentrated by sedimentary chemical or biochemical processes, is associated with fine-grained carbonaceous shale or phosphorite, never with coarse clastics.

Dispersed sources within the sedimentary column as a whole seem ample to supply the volume of metals in even more extensive ore deposits than those already known. Moreover, circulating ground water probably would not be far out of equilibrium with the sediments and hence would not produce the marked alteration effects expected of hydrothermal solutions but not observed in the field. That the process is a workable one is suggested by Denson and others, who present strong evidence to show that the uranium in lignites in North and South Dakota has been derived from volcanic ash in overlying beds. The hypothesis of a dispersed source has not been considered with respect to the Rand ores, and no evidence is available on which to appraise its merits. The isotopic data, however, cast some light on the source of the Plateau ores. According to Stieff and Stern, the uranium ores, the galena associated with the



deposits, the lead in Tertiary vein deposits in the San Juan Mountains, the Colorado Front Range, and the Tucson Mountains of Arizona, all contain lead that has the same peculiar isotopic composition or that varies systematically from this composition in a manner expectable by the addition of differing amounts of  $\text{Pb}^{206}$  and  $\text{Pb}^{207}$  produced by the decay of uranium. The additional uranogenic lead was formed before its deposition in Tertiary rock. Because this lead has a high 207/206 ratio it must contain an increment of lead derived from old radiogenic sources poor in thorium or from sources that have not released much thorium lead. The uniform composition of the lead in these several types of deposits suggests that they have a common source. From the presence of this lead in the Tertiary veins it seems most reasonable to assume that this pre-Cambrian source lay at depth, possibly in pre-Cambrian thorium-poor, uranium-rich bodies in the basement complex. Syngenetic or penecontemporaneous derivation of the ore from the volcanic ash in the Triassic and Jurassic sediments is improbable, because ores in these rocks do not show isotopic differences which would be expected if radiogenic lead that had formed in the ash before the uranium was removed from the tuffs was added. The isotopic data alone do not rule out the possibility that the ores might have been derived from a single source in the rocks above the deposits, but the presence of lead in the Tertiary veins and the fact that many of the deposits lie several thousand feet below the Tertiary make such a source improbable. Because the possibility of lateral secretion on such a grand scale as that required to form the Plateau and Rand deposits has been little explored, the hypothesis of a dispersed source probably deserves further consideration. The isotopic data, however, seem to make it an improbable explanation for the ores of the Colorado Plateau.

The occurrence of uraniferous "asphaltite" in oil-stained pore spaces, and the similarity of the assemblage of other metals in some asphaltites to that found in smaller concentrations in oil in nearby pools, led Gott and Erickson to the conclusions that "asphaltite" is residual petroleum and that petroleum fluids may transport uranium to sites of ore deposition, particularly in sandstone-type deposits. Goldschmidt postulates a similar source and history for vanadium and other metals in petroleum and asphalts. Crude oils may contain a fraction of a part per billion ( $10^{-9}$ ) to a few thousand parts per billion, most of which seems to be in asphaltenes, but a few analyses of the Plateau oils indicate that the higher concentrations are only in oil that has penetrated a uraniferous sandstone. Oil is not common on the Plateau and is unknown in the Witwatersrand system. "Asphaltite" on the Plateau is common in only a few areas (much "asphaltite" is proving to be woody material), and the thucholite in the Rand ores bears a replacement relationship to early uraninite. For these reasons it seems unlikely that migrating petroleum is the source of much if any of the uranium on the Plateau or the Rand. It is possible, however,



that some uranium in both areas may have been transported short distances by fluid hydrocarbons.

Several lines of evidence have been cited to support a hydrothermal source for both Plateau and Rand ores: (1) Both contain ore minerals—uraninite, sulfides, etc.—typical of other hydrothermal deposits. (2) The gangue minerals—quartz (mainly as overgrowths but also in veins in the Rand), chlorite, and clay minerals—are typical of or not incompatible with a hydrothermal association. (3) Evidence of movement of mineralizing solutions in the form of altered dikes, vein quartz, and sulfides is found along cross-cutting fractures and dikes in the Rand, and some Plateau ores, particularly those high in copper, are associated with faults or fractures. (4) The uranium content of the sandstone ores is similar to that of other hydrothermal ores and dissimilar to that in deposits of other origins. (5) The ores in some parts of the Plateau are zonally arranged around laccolithic intrusives. (6) Isotopic data show the Plateau ores, which include vein copper deposits and limestone replacement ores as well as the more abundant and typical “bedded” deposits in sandstone, to be genetically related to vein deposits of uranium in the same general region.

Some of these features may be explainable in other ways, but one or another of them has been compelling enough to cause syngeneticists in both areas to admit that some of the deposits or some minerals in them are hydrothermal. The arguments have not been accepted for other deposits or minerals mainly because (1) most of the ores show no relation to structural or igneous features; (2) the host rocks are not as conspicuously altered as are most hydrothermal deposits, and (3) vanadium, an important component of some of the Plateau ores, is not an important mineral in other hydrothermal deposits. Those favoring a hypogene source admit the close relation to sedimentary features but believe that in the absence of fractures, solution movement would be controlled by the directional permeability of the rock. They believe that the lack of alteration is more apparent than real, and because vanadium is a constituent of some vein deposits, they do not consider its presence in some of the Plateau ores a valid objection to the hydrothermal hypothesis. They thus imagine the deposits to be bedded or “interstitial” quartz-sulfide veins, differing from hydrothermal veins only in that they occupy pore spaces in sandstones instead of fractures.

The specific source of the hydrothermal solutions is problematical. The Plateau deposits show some spatial relationship to laccolithic intrusives; but intrusives are not widespread on the Rand, though alkalic granites intrude the Witwatersrand system at Vredfort, southwest of the Rand. Nevertheless, Davidson points out that the Rand deposits, as well as those of the Plateau, the copper-cobalt-uranium ores of the Belgian Congo, and the uranium-copper deposits of Rum Jungle in Australia, are in a group of sediments that overlie



a complex of Archean granites which "have undergone domal uplift since the covering blanket of sediments was deposited, due presumably to 'younger' granites which are not always exposed. . . . May it not be that the ore deposits in each of these regions represent a 'front' of mineralization which has emanated, through the older granites from the younger magma below?"

The sum total of the available evidence indicates to us that the deposits were derived from a deep-seated source and transported along fractures to permeable horizons, which they then followed to the site of deposition. The mineral assemblage and fine-grained texture of the ores suggest deposition at relatively low temperature and pressure, possibly in the range normal for water-saturated rocks buried by several thousand feet of sediments. Thus if a normal geothermal gradient prevailed at the time of deposition of the Plateau ores, the temperature in the host rocks probably was in the range of 70° to 120°C and the pressure in the range of 200 to 800 atmospheres (the range between the hydrostatic and lithostatic load). As to the chemical factors that led to the precipitation of the ore minerals, the low-valence state of the primary minerals suggests that precipitation probably was brought about by reduction, possibly by decaying carbonaceous matter. Sedimentary structures also played an important role in the localization of the ore. The lenticularity of permeable facies served to prevent solutions from dispersing so widely that no appreciable concentration of metals could result on precipitation. In addition, as shown by the common occurrence of ore at bends in fossil stream channels and along the margins of the more permeable zones, certain structures acted as traps for ore. The mechanics of these traps is not understood; it is possible that their lower permeability lowered the velocity of percolating ore solutions sufficiently to allow time for precipitates to form and become fixed, possibly as replacements of organic matter, clay, and other matrix material.

#### URANIFEROUS COAL AND ASSOCIATED CARBONACEOUS SHALE

Coal and associated carbonaceous shale beds are generally nonuraniferous, but some rather extensive beds in western United States and elsewhere contain 0.005% to about 0.1% uranium, and a few in South Dakota contain 0.2% uranium or more. Most of the uraniferous coals are rather high in ash content and low in rank. Secondary uranium minerals, such as autunite, meta-autunite, metatyuyamunite, and uranocircite are found in some of the higher-grade deposits, but the uranium in lower-grade deposits is in dispersed form, at least in part in organouranium complexes or ionic organic compounds. In individual specimens of low-grade coals, the uranium is fairly uniformly distributed, but in larger bodies the uranium content is irregular. In their studies of lignites in South Dakota, Denson, Bachman, and Zeller found that



in most places only the first lignite immediately below the tuffaceous White River formation of Oligocene age, which unconformably overlies the coal-bearing strata there, is appreciably uraniferous. Moreover, the uranium content of a given layer is highest at the top. Concentrations of uranium may be found in lower beds adjacent to faults or through-going joints, or where they are in contact with a pervious sandstone layer. These relationships have been found to characterize several other uraniferous coals in western United States.

The problems of the origin of uranium in coal and carbonaceous shales are analogous to those of the sandstone ores but are perhaps not as complex. Because certain land plants concentrate enough uranium to be of value in prospecting for ore deposits, it might be supposed that uranium in coal is concentrated by living plants. It appears, however, that significant concentrations of uranium—1 ppm or more in the ash—are found only in plants growing on mineralized ground. Even there it is exceptional to find a uranium content of 100 ppm in the ash, an amount common in the ash of uraniferous lignites and carbonaceous shales. It thus seems unlikely that the uranium in coaly beds was first concentrated by living plants. Moreover, the irregular distribution of uranium in the individual beds, its regional relationship to unconformities, its vertical distribution within individual beds, and its local concentration along fractures and permeable beds indicate that it was introduced after deposition of the enclosing rocks, though its even distribution in individual specimens suggests that it was introduced prior to coalification.

The source of the uranium is more debatable and may be different from place to place. Because of the relationships already described, Denson and his colleagues concluded that the uranium in the Dakota lignites was derived from uraniferous tuffaceous materials in the White River formation. The presence of uraniferous bones in the White River as well as the relatively high amounts of uranium in ground water draining from the White River formation tend to support this view. Similar sources have been suggested for uranium in several other uraniferous coals in the western United States. Other sources besides tuff, such as decaying granitic or arkosic rocks or hydrothermal solutions, might be the source of uranium in other deposits. Thus Turner postulated that the uranium in peat deposits in Madagascar came from the decomposition of nearby titano-niobates\* and L. R. Page suggested that the uranium in a coal bed cut by a shear zone in the Old Leyden mine at the foot of the Colorado Front Range probably was derived from hydrothermal solutions.

The uraniferous waters now draining certain tuffaceous terranes are con-

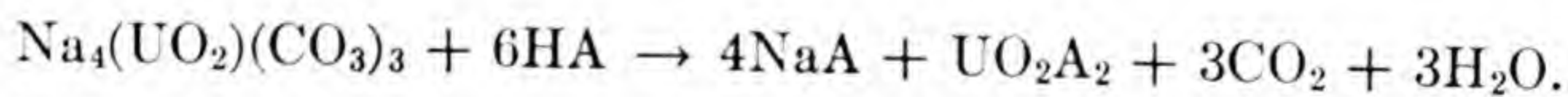
\* Because these minerals are ordinarily resistant to weathering, it seems more probable that the uranium in these deposits was derived from rhyolitic pumice, which is reported to occur in the alluvium of which the peats are a part.



ceivably similar to solutions from which the uranium in coals was derived. They contain as much as 0.5 ppm uranium (ordinary waters contain less than 0.001 ppm), several hundred parts per million of sulfate or bicarbonate or both, are very high in total dissolved solids, and are moderately alkaline. Because source solutions are thus dilute, the formation of a large uraniferous coal deposit probably takes a long period of time, for the coal must be exposed to a considerable volume of a solution so dilute. Moreover, many coals are not pervious enough to permit passage of large volumes of solution. Thus Breger and Deul were unable to pass water through a column of —50 mesh subbituminous coal, even under a pressure of 15 psi of nitrogen, without mixing diatomaceous earth with the coal to increase its permeability. As Gott and others assumed for other reasons, this may mean that introduction of uranium must take place before coalification. It is possible too that permeability relationships account for the concentration of uranium at the top or base of many beds and for its relative enrichment in high-ash beds.

The deposition of the uranium in coal doubtless took place by chemical reaction or adsorption. Szalay has shown that brown coal will absorb uranium from a solution of potassium uranyl carbonate. Moore found that subbituminous coal, lignite, and peat irreversibly removed more than 98% of the uranium from a solution containing 196 ppm U (in the form of  $\text{UO}_2\text{SO}_4$ ) to which they were exposed for twelve days. Under the same conditions, wood adsorbed 40% of the uranium, a bituminous coal 17%, an anthracite 34%, graphite 28%, charcoal 31%, canneloid coal 80%, and silica flour none. On the basis of these results, Moore concluded that the uranium is precipitated as a metallo-organic compound. Breger, Deul, and Rubinstein, after noting that the pH of several lignites from the western states is less than 6.5, observed that

. . . certain alkaline uranyl carbonates and alkaline-earth carbonates are extremely soluble in water. Typical compounds are  $\text{Na}_4(\text{UO}_2)(\text{CO}_3)_3$ ,  $\text{Na}_6(\text{UO}_2)_2(\text{CO}_3)_5$ , and  $\text{Mg}(\text{UO}_2)(\text{CO}_3)_3$ . These compounds are sensitive to acids and break up with the release of carbon dioxide. If such a uranium-bearing solution came into contact with a lignite, a zone of low pH, the following type of reaction would be expected:



The acids from the lignite, represented by HA, are unknown in structure and, for the sake of balancing the above equation, are assumed to be monobasic. It is conceivable that a compound such as  $\text{UO}_2\text{A}_2$  might be insoluble above pH 2.18. This is a suggested process to account for the introduction and retention of the uranium in a coal.



## URANIFEROUS BLACK SHALE

Many marine black shales contain 0.005% to 0.02% uranium. The uranium is in acid-soluble form, but it probably does not occur in a distinct uranium mineral. In the Devonian and Mississippian Chattanooga shale of Tennessee, autoradiograph studies show that the uranium is in organic matter-pyrite complexes. The highest uranium content (as much as 0.5%) in the Cambrian alum shale of Sweden is in lenses of dark bitumen called "kolm"; the megascopic lenses do not contain an appreciable proportion of the total uranium in the shale, but microscopic particles of similar material may be the principal carrier of uranium in the shale matrix. In the Miocene nodular shale in California and the Pennsylvanian Cherokee shale equivalents in Oklahoma, the uranium may occur both in carbonaceous matter and phosphate. Because the uranium content increases directly with increasing percentages of carbon in many shales, Fredrickson suggests that the  $(U^{VI}O_2)^{++}$  ion "is adsorbed between the graphite layers of carbonaceous material, forming a strong structure due to the stable  $UO_2^{++}$  ion holding the two layers together."

As a group the uraniferous marine black shales are highly carbonaceous and bituminous, high in sulfides, noncalcareous, somewhat phosphatic (or contain phosphatic nodules in the section) and thin for the period of time they represent. In vertical sequences, the uraniferous black shales are associated with phosphatic rocks, chert, carbonate rock, and sandstone. The black shales are not appreciably uraniferous, however, where thick, high-grade phosphorite beds are present. The richest parts of the Swedish shale are in the middle or upper part of the shale sequence, in or closely adjacent to that part of the sequence which contains maximum amounts of distillable oil, total organic matter, pyrite, and kolm; areally, the richest parts are in tongues, interpreted as embayments in the Upper Cambrian sea.

The problem of the origin of the uranium in the marine black shales is more one of the environment, manner, and causes of precipitation than one of the time of deposition of the uranium compared to that of the host rock or the source of the uranium. Although it is generally assumed that the uranium in these beds is syngenetic, in view of the capacity of carbonaceous materials to adsorb uranium, it is possible that some of the uranium may have been adsorbed after deposition, either from sea water or from water released from other sediments during compaction. Uranium in waters draining overlying beds might be adsorbed also, but because this would not take place until after compaction and perhaps lithification, uranium derived in this way might be concentrated along joints, a phenomenon rarely observed in the marine black shales.

Although most of the uranium in the shales is derived directly or indirectly



from sea water, which contains  $1.0\text{--}1.8 \times 10^{-6}$  grams of uranium per liter, the question arises whether the uranium has been derived locally or brought to the site of deposition through oceanic circulation. Glebov and Strøm postulate that uranium is derived from adjacent terranes, presumably during periods when chemical weathering is the dominant process of erosion. This is a reasonable assumption if the basins of deposition are restricted embayments, and it may account for the uranium content of the alum shale, the most uraniferous parts of which apparently were deposited in embayments not far from a granitic terrane. It seems unlikely, however, that local sources contributed much of the uranium found in the more widespread black shales, such as the Chattanooga. Moreover, because the uranium content of ocean waters and large river waters is about the same—ocean waters range from about  $1.1 \times 10^{-6}$  gm/liter in surface waters to  $1.3$  or  $1.4 \times 10^{-6}$  gm/liter in deeper waters; river waters range from about  $0.3$  to  $20 \times 10^{-6}$  gm/liter but none of any size contain more than  $1$  or  $2 \times 10^{-6}$  gm/liter—the identification of source of the uranium in black shales does not seem of critical significance.

Of more importance may be the environment of deposition. The rocks of the phosphorite family of sediments, to which the black shales belong, are generally deposited on a shelving bottom where cold waters rich in phosphate, nitrate, and possibly other elements whose solubility is influenced by pH, upwell from oceanic depths. As these waters are warmed, some of the dissolved substances become insoluble and are chemically precipitated or removed from the sea by organisms. The nutrients in these upwelling waters fertilize the upper waters of the sea, producing tremendous blooms of plankton that lead to the development of an anaerobic sapropel on the sea bottom, even in the open ocean. Nutrient-rich fresh waters draining into a restricted embayment may produce the same effect. The close relationship between the maximum amounts of uranium, oil, total organic matter, and sulfides, as well as the concentration of uranium in some shales in embayments or near their margins of deposition, suggests that the formation of a highly reducing environment may be a prerequisite to the concentration of uranium in the shales. According to Goldschmidt, precipitation of uranium in black shales "might result from a reduction of sexivalent uranium to the quadrivalent stage by the action of hydrogen sulfide in stagnant bottom waters. . . . We may therefore expect accumulation of the solute uranium from sea water by reprecipitation in areas where strongly reducing conditions prevail." It seems probable that appreciable deposition or preservation of uranium takes place only when the pH and  $E_H^*$  lie within narrow limits—limits that may be approached closely enough in the deposition of ordinary black shales to permit the formation of some sulfides and the preservation of some organic matter, but that are reached only rarely.

\* Oxidation potential. [Ed.]



Deposition of uranium in the shales might have taken place in one or both of two ways, (1) direct precipitation or (2) chemical adsorption by organic matter (living or dead) or by apatite. The absence of any uranium mineral in the shales argues against direct precipitation. Some marine algae, however, concentrate minor metals, and dead plankton is reported to be an effective adsorbent for uranium and other metals. Most of the uranium in apatite is thought to be removed from the sea by adsorption, and possibly some of the uranium in the shales may also have been adsorbed by phosphatic materials. Even though biochemical precipitation or adsorption may be the chief mechanisms of deposition of uranium in the shales, these processes are not likely to be effective in the permanent removal of uranium from the sea unless chemical conditions favor or approach those necessary for direct precipitation of uranium. It is possible, however, that organisms may remove uranium from the upper waters of the sea, where reducing conditions do not prevail, and after death carry it to the bottom where the reducing conditions necessary for the retention of uranium do exist.

The uranium in the hydrocarbons in the black shales probably enters these compounds after deposition. Smith, in reporting his discovery of oil in recent sediments, adopts F. C. Whitmore's earlier hypothesis that "the generation of petroleum is very largely a process of selection and concentration of hydrocarbons originally synthesized by the metabolism of marine (or even terrestrial) plants." Collection and concentration of the hydrocarbons probably begins shortly after burial, and minor metals probably are dissolved at this stage.

#### URANIFEROUS MARINE PHOSPHORITES

Marine phosphorites contain 0.005% to 0.03% uranium. Traces of secondary uranium minerals are occasionally found in weathered deposits but most of the uranium is in dispersed form. It is acid-soluble, tetravalent, and seems to be in the mineral carbonate-fluorapatite, where it probably substitutes for calcium. Although there are numerous exceptions, the uranium content of the phosphorites increases roughly as the phosphate content increases, but in the Permian Phosphoria formation at least, the uranium content falls off rapidly as the  $\text{CO}_2$  content rises above 3% or 4%, regardless of the phosphate content. Phosphatic limestones are thus only weakly uraniferous, but phosphatic nodules in certain black shales are uraniferous, generally more so than the enclosing shale. Black shales associated with the phosphorite formations are only weakly uraniferous. Fossil bones and teeth contain as much as 0.5% U without showing a separate mineral phase and the uranium content seems to be greater in older than in younger species. In the Phosphoria formation, however, beds composed of organic fragments are less uraniferous than other kinds of phosphatic materials.



As with the black shales, much of the uranium in the phosphorites and phosphatic nodules probably was derived from sea water at or shortly after the time the rocks were deposited. Because the phosphorites are more permeable than the shales, more of the uranium in the phosphorites may have been derived from later solutions, or redissolved and redeposited by them.

The environment of deposition of the marine phosphorites is much the same as that of the black shales with which they are associated, except that the phosphorites probably accumulate in shallower, more aerated water. The negligible uranium content of modern bones and the absence of a separate uranium mineral indicate that precipitation of uranium in the phosphorites must have taken place not by biologic activity or direct precipitation but by one or another of the processes known as chemical adsorption—perhaps co-precipitation, or isomorphous substitution of uranium for calcium at some time after the deposition of carbonate-fluorapatite. The efficacy of this process has been shown by Moore, who found that phosphate rock removed 63% of the uranium present in a solution of  $\text{UO}_2\text{SO}_4$  containing 196 ppm U; and by Neuman and others, who demonstrated that bone (which consists of hydroxyapatite) can adsorb as much as 4.8% U from a dilute, bicarbonate-buffered solution of uranyl acetate, replacing calcium at the surface of the apatite crystal. Other experiments show that the precipitation of uranium in bone ash decreases with increase in calcium and increase in bicarbonate ions in solution and with increasing pH, from 6.5 to 8.0. These results indicate “that a direct competition exists between calcium and uranium for the combining sites on the bone phase . . . between carbonate ion (which forms a relatively undissociated complex with uranyl ion) and the surface phosphate groups for uranium. The reduced uranium adsorption observed at elevated pH is somewhat more complicated but, in part, may be viewed as a competition between surface phosphate groups and hydroxyl ions.” Inasmuch as the uranium in the phosphorites is tetravalent, a reduction reaction must be involved in its precipitation.

Variation in the uranium content of phosphorites of similar  $\text{P}_2\text{O}_5$  content may arise in part from differences in the uranium content of the sea water at the time of deposition, but the most significant variations probably result from differences in the pH, calcium, and carbonate ion concentration of the source water, the length of time phosphate particles are exposed to the sea before burial, and their postdepositional history.

#### SELECTED REFERENCES FOR CHAPTER 3

- Adams, J. A. S., 1954: Uranium and thorium contents of volcanic rocks. In H. Faul (Ed.), *Nuclear Geology*. New York, John Wiley & Sons, Inc., pp. 89–98.
- Altschuler, Z. S., R. S. Clarke, Jr., and E. J. Young, 1954: Uranium in apatite. *Geol. Soc. Am. Bull.* 65:1225 [Abstract].



- Bates, T. F., E. O. Strahl, N. M. Short, E. N. Silverman, and E. Camilli, 1954: Mineralogy and petrography of the Chattanooga shale. *Geol. Soc. Am. Bull.* 65:1230.
- Breger, I. A., M. Deul, and S. Rubinstein, 1955: Geochemistry and mineralogy of a uraniferous lignite. *Econ. Geol.* 50:206-226.
- Davidson, C. F., 1953: The gold-uranium ores of the Witwatersrand. *Min. Mag.* 88:73-85.
- 1954: Discussion. *Inst. Mining & Metallurgy Bull.*, February 1954, p. 247.
- Davidson, C. F., and D. Atkin, 1953: On the occurrence of uranium in phosphate rocks. Algiers, 19th Internat. Geol. Congr. *Compt. Rend.* 11:13-31.
- Davidson, C. F., and D. R. A. Ponsford, 1954: On the occurrence of uranium in coals. *Min. Mag.* 91:265-273.
- Erickson, R. L., A. T. Myers, and C. A. Horr, 1954: Association of uranium and other metals with crude oil, asphalt, and petroliferous rock. *Am. Assoc. Petrol. Geol.* 38:2200-2218.
- Garrels, R. M., and D. H. Richter, 1955: Is carbon dioxide an ore-forming fluid under shallow earth conditions? *Econ. Geol.* (in press).
- Goldschmidt, V. M., 1954: *Geochemistry*. Ed. by Alex Muir. Oxford, Clarendon Press.
- Gruner, J. W., 1954: The origin of the uranium deposits on the Colorado Plateau and adjacent regions. *Min. Mag.* 44: 53-56.
- Katz, J. J., and E. Rabinowitch, 1951: *The Chemistry of Uranium*. New York, McGraw-Hill Book Company, Inc.
- Lang, S. M., 1953: *Solid State Reactions of the Uranium Oxides*. National Bureau of Standards Circular 535.
- Larsen, E. S., Jr., N. B. Keevil, and H. C. Harrison, 1952: Method for determining the age of igneous rocks, using the accessory minerals. *Geol. Soc. Am. Bull.* 63:1045-1052.
- Larsen, E. S., Jr., and George Phair, 1954: The distribution of uranium and thorium in igneous rocks. In H. Faul (Ed.), *Nuclear Geology*. New York, John Wiley & Sons, Inc., pp. 75-89.
- Louw, J. D., 1954: *Geological Age Determinations on Witwatersrand Uraninites Using the Lead Isotope Method*. Geological Society of South Africa, pp. 1-19 (advance proof).
- McKelvey, V. E., 1955: *Search for Uranium in the United States*. U.S. Geological Survey Bull. 1030A.
- McKelvey, V. E., D. L. Everhart, and R. M. Garrels, 1955: The origin of uranium deposits. *Society of Economic Geologists 50th Anniversary Volume*.
- Miller, R. L., and J. R. Gill, 1954: Uranium from coal. *Scientific American* 191:36-39.
- Moore, G. W., 1954: Extraction of uranium from cold water solutions by coal and other materials. *Econ. Geol.* 49:652-658.
- Page, L. R., 1950: Uranium in pegmatites. *Econ. Geol.* 45:12-34.
- Runnels, R. T., J. A. Schleicher, and H. S. Van Nortwick, 1953: Composition of some uranium-bearing phosphate nodules from Kansas shales. *Kansas Geol. Survey Bull.* 102:93-104.
- Stieff, L. R., T. W. Stern, and R. G. Milkey, 1953: *A Preliminary Determination of the Age of Some Uranium Ores of the Colorado Plateaus by the Lead-Uranium Method*. U.S. Geological Survey Circular 271.
- Szalay, S., 1954: The enrichment of uranium in some brown coals in Hungary. *Acta geologica Hungarica* 2:299-310.
- Waters, A. C., and H. C. Granger, 1953: *Volcanic Debris in Uraniferous Sandstones, and Its Possible Bearing on the Origin and Precipitation of Uranium*. U.S. Geological Survey Circular 224.



# *Chapter 4*

---

## URANIUM PROVINCES \*

---

As with many other metals, most of the world's important uranium deposits are clustered within broad, indefinitely defined areas or provinces. The initial concentration of uranium in these broad areas probably occurred during the formation of the earth's crust. Subsequently, owing to the interplay of geochemical and orogenic processes, the uranium in the original areas of concentration has been redistributed and in part concentrated to exploitable deposits.

A uranium province is here defined as a broad and generally indefinitely bounded area in which uranium deposits and uranium-rich rocks are relatively abundant. Commonly, the deposits are of several types and of more than one age. Most of the world's important uranium deposits are clustered in a few such areas; notably the broad belt in and adjacent to the Rocky Mountains, from New Mexico and Arizona to the Dakotas and Montana; the western and southern part of the Canadian Shield; the eastern part of the South African Shield; the Erzgebirge and vicinity in central Europe; and probably the Ferghana-Kara Tau region in Russia.

In contrast there are broad areas in which uranium deposits, other than low-grade syngenetic concentrations in phosphorite or black shale, are sparse or lacking. For example, in the eastern third of the United States, in and adjacent to the Appalachian Mountains, no important uranium deposits are known, though there are low-grade syngenetic concentrations in black shale and scattered pegmatites, and a few small epigenetic deposits of carnotite in sandstone.

The main geologic features of the uranium-poor Appalachian region are in many respects similar to those of the uranium-rich Erzgebirge and Rocky Mountain regions. Each of these areas is a strongly deformed geosynclinal belt, intruded by granitic plutons of various types; each is flanked and in

\* From Geneva Conference Paper 14, "Uranium Provinces" by M. R. Klepper and D. G. Wyant, U.S. Geological Survey.

Selected references for this chapter are listed alphabetically by author at the end of the chapter.



part covered by erosional debris from orogenic mountains. The Triassic basins and the plateaus underlain by Pennsylvanian nonmarine rocks in the Appalachian region are comparable to the plateaus and intermontane basins within and adjacent to the Rocky Mountains and to the Triassic and younger basins and plains marginal to the Erzgebirge. Nevertheless, in the Appalachian region, uranium concentrations are few, low-grade, and mostly of syngenetic origin (black shale and pegmatite), whereas in the Rocky Mountain region, important epigenetic deposits of several types occur in many districts. In the Erzgebirge region, veins have been an important source of uranium for many years, and strongly uraniferous coal has recently been reported.

Similarly, the geologic histories and features of the Canadian Shield, the South African Shield, the Fennoscandian Shield, and the Brazilian Shield are roughly similar, but the first two contain important uranium deposits, whereas the last two contain virtually no known deposits.\*

#### PROCESSES THAT CONCENTRATE URANIUM

The formation of exploitable uranium concentrations in a uranium province depends on many geologic factors. The processes involved are largely geochemical, though to a large extent they are actuated by orogenic events.

The concept of the geochemical cycle, though idealized and imperfectly known, provides a means of relating the processes that concentrate uranium to the geologic or orogenic history of an area and thus can be used to predict where concentrations of uranium are likely to occur and what the potential of a particular area may be. It is convenient to think of the geochemical cycle as consisting of three phases that grade into one another: (1) one in which igneous processes prevail, (2) one in which weathering and sedimentary processes prevail, and (3) one in which metamorphic processes prevail. During the igneous and metamorphic phases of the cycle, magma is generated, emplaced, and consolidated, pre-existing rocks are metamorphosed, and uranium deposits of igneous and metamorphic origin may be formed. During the weathering and sedimentary phases, pre-existing rocks and ore deposits are weathered and eroded, uranium is transported and may be concentrated, and sediments accumulate and are lithified.

The formation of a magma, the upward movement and crystallization, and the subsequent exposure of the resulting igneous rock are a part of the orogenic cycle. The uranium content of the rocks formed from a magma increases rather constantly from the first- to the last-formed rocks and thus in a general way follows the same path as silica, the alkalis, and rare elements such as thorium, beryllium, columbium, tantalum, and the rare earths.

\* Recently discovered uranium deposits of undetermined importance near Jacobina, Bahia, Brazil, are similar in many respects to the uraniferous gold reefs of South Africa. [Ed.]



The earliest differentiates consist chiefly of olivine, pyroxene, and calcic plagioclase, minerals that tolerate only negligible quantities of uranium in their lattices. Consequently, these rocks generally contain less than 1 ppm uranium. Later differentiates contain significant amounts of biotite and accessory minerals. Some of these minerals can accommodate in their lattices from 10 ppm to a few per cent uranium; and the rocks, such as granodiorites, syenites, and granites, contain from 2 to 6 ppm uranium. The youngest rocks in some alkalic and silica-alkalic series, for example albite-rich riebeckite granite in Nigeria, quartz bostonite in Colorado, and pegmatites from many widely scattered localities, contain from 10 to 100 ppm (0.001% to 0.01%) uranium.

Recent investigations suggest that effusive rocks are generally more uraniferous than their intrusive equivalents, possibly by a factor of  $1\frac{1}{2}$  or 2. The uranium content increases as potassium increases and the uranium content becomes progressively higher in more acidic rocks. Perhaps the best explanation of the higher average uranium content of effusive rocks is that most of the uranium is trapped in dispersed form during the crystallization of effusive magmas, whereas a significant part of the uranium in plutonic magmas is concentrated in residual fluids from which pegmatites and veins may form. This interpretation agrees with the generally held belief that the most favorable settings for hydrothermal deposits of uranium are in the vicinity of plutons of acidic rock.

In some of the relatively uraniferous igneous rocks, most of the uranium is in the rather common accessory minerals, notably xenotime, zircon, monazite, and allanite. In others, most of it is in relatively uncommon uranium-rich accessory minerals such as uraninite, thorite, thorianite, brannerite, and euxenite.

Most igneous rocks also contain uranium in a form that is readily soluble in weak acids. Hurley found that as much as 90% of the total radioactivity of some granites could be removed by leaching the granulated rock with weak acid. He postulated that the acid-soluble radioactivity was present along fractures and on grain surfaces and may have been due to "supergene enrichment." Larsen and Phair note that "commonly, close to 40 per cent of the uranium in most fresh-appearing igneous rocks is readily leachable." They suggest that this leachable radioactivity may occur "(1) in metamict phases of primary silicates (presumably such accessories as zircon, allanite, and thorite), (2) as interstitial material derived from late magmatic, deuteric, or hydrothermal solutions, (3) in certain non-metamict partly soluble radioactive accessories, such as apatite, and (4) as adsorbed ions in disseminated weathering products such as iron oxide." Bowie, using autoradiographs, found that "in an unaltered granite the heavy minerals [accessories] account for nearly all the radioactivity," but "in rocks slightly altered by pneumatolysis or by ground waters the radioactive



elements become distributed along cracks within and as coatings to the feldspars and quartz."

Though the origin and nature of this acid-soluble material is not yet established, its presence has several important implications. First, it suggests that significant quantities of uranium can be leached from igneous rocks by ground water and perhaps later be concentrated as secondary deposits in coal or other sedimentary rocks. Secondly, the possibility that some of this acid-soluble material may be a sample of the residual fluids of a magma suggests that a close relationship may exist between the acid-soluble uranium in igneous rocks and uranium in veins and other types of epigenetic deposits.

Veins and other epigenetic uranium deposits of igneous origin are believed to have formed from the late differentiates of a uranium-rich magma where structural conditions were favorable. Thus much of the uranium-rich residual fluid probably drained off to form veins if through-going fractures tapped the magma chamber at the proper time. If fractures did not tap the chamber at an opportune time, most of the uranium in the residual fluids was probably trapped in the last igneous rocks to crystallize, partly in specific uranium-rich minerals and partly as soluble intergranular films.

Information on the relationship of abnormally uraniferous igneous rocks and hydrothermal deposits of uranium is meager. Bain noted a lack of hydrothermal uranium deposits in areas containing uraniferous pegmatites, but many examples can now be cited of close association of abnormally uraniferous igneous rocks, including pegmatites, with hydrothermal uranium deposits. Some examples are:

1. In the Colorado Front Range, late Cretaceous or early Tertiary pitchblende veins are intimately associated and probably genetically related to uraniferous quartz bostonites. Some pitchblende veins of this same age also occur in the vicinity of uraniferous pre-Cambrian pegmatites.
2. In the Erzgebirge and Riesengebirge of Saxony, Silesia, and Czechoslovakia uraniferous granite, uraniferous pegmatite, and pitchblende veins are closely associated.
3. In the pre-Cambrian shield of Canada, uraninite-bearing pegmatites and pitchblende veins are in close association, though they may not be of the same age, in the Goldfields region and at Stack Lake on the east arm of Great Slave Lake; furthermore, the important uraniferous pegmatite at Charlebois Lake is only about 100 miles east of the Goldfields pitchblende veins. In the Grenville subprovince, uraniferous pegmatites are abundant and pitchblende veins occur, though none of them are at present commercially important; important uraniferous carbonatites (calcite-fluorite pegmatites) also occur near Bancroft in this subprovince.



Though these examples are too few to fully support a generalization, the writers are inclined to agree with Lang that abnormally radioactive igneous rocks may be indicators of nearby hydrothermal uranium deposits. However, they are not necessarily so, for tectonic events during the late stage of magmatic consolidation probably determine to a large extent whether most of the uranium in the residual magmatic fluids crystallizes in late-stage igneous rocks, such as pegmatites, or in veins or in both. If most of the uranium was drained off at a late stage to form veins, the associated igneous rocks may not be abnormally uraniferous.

Destruction by weathering and erosion of uranium-rich igneous rocks and veins, and of uranium concentrations in sedimentary and metamorphic rocks, releases uranium that may be either swept out of the province or reconcentrated in suitable environments.

Whether uranium is retained or exported from a province appears to depend largely on the climate, topography, and lithology of the area. Climate is probably the most important factor. In a humid climate the water table is high, weathering is intense, and the products of weathering tend to be clay minerals. As the drainage is to the sea, the uranium, whether in solution or adsorbed on particles of clay minerals, will be permanently removed from the uranium province.

At the other extreme, in an arid climate, water tables are far below the surface or are nonexistent. Weathering tends to simply disaggregate existing rocks, and drainage is either intermittent toward the sea or centripetal. In such an environment the uranium brought near the surface by igneous activity cannot be readily exported from the area. Rain that extracts uranium from outcrops of igneous rocks or veins soon sinks deep into the soil or subsoil and may follow subterranean channels for great distances. In so doing it may traverse favorable lithologic types, and the uranium may be redeposited in new and perhaps much richer concentrations. Clay minerals do not form in great quantities, and little uranium is lost by adsorption in clay particles. Certainly the western United States and the Ferghana-Kara Tau area owe many of their secondary uranium concentrations to favorable arid climatic conditions that have prevailed for many millions of years.

Soluble uranium in ground and surface waters may be extracted by organisms and incorporated in their tissues; precipitated as secondary minerals such as carnotite and schroëckerite; adsorbed or absorbed by certain clays, organic and phosphatic material, and colloidal silica; or extracted to form metallo-organic compounds in petroleum. The deposits so formed include most uraniferous peat, lignite, coal, and petroleum residue, and many deposits of secondary uranium or complex metal-uranyl phosphates, carbonates, vanadates, sulfates, arsenates, etc. In many instances, as for example on the Colorado Plateau, it is not clear whether deposits consisting of secondary minerals have been



formed by oxidation of a primary deposit more or less *in situ* or by precipitation of uranium from migrating solutions in favorable geologic settings.

Whether useful concentrations of uranium are precipitated from migrating solutions is probably largely dependent on the amount of uranium in the carrier, the continuity of flow within a restricted area over a long enough period of time, and the presence of suitable receptors or reagents or of favorable physical conditions, such as alternate wetting and drying, to remove it from solution.

Many minerals that contain small to moderate amounts of uranium, such as monazite, zircon, xenotime, brannerite, samarskite, and euxenite, are relatively resistant to chemical and mechanical attack. These resistant minerals locally become concentrated in fluvial or marine placer deposits in the vicinity of the source rocks, but most of them become dispersed in terrestrial and near-shore marine sediments without significant concentration. Placers are typically ephemeral, but a few persist and become lithified. Some geologists contend that the uraniferous Witwatersrand and Blind River conglomerates of Africa and Canada are fossil placer accumulations that have been subsequently modified and perhaps enriched by hydrothermal solutions; others contend that the deposits cannot be placers; some strongly advocate a hydrothermal origin.

Sedimentary rocks, when deeply buried, generally during the deformation of geosynclines, are transformed to a rock or liquid that is in equilibrium with its surroundings. At various depths and under the influence of various pressures, either hydrostatic or directed, the rocks are metamorphosed to gneisses, schists, hornfels, etc., and under extreme conditions are probably liquified to magma. As a result of these processes, fractionation and concentration of uranium may take place. In the melting of rocks the first liquid to form should resemble the last liquid fraction of a magma and be rich in silica, potash, alumina, and water, and probably also in uranium and other minor elements that tend to concentrate in residual granitic fluids. If this is so, some magmas produced by ultrametamorphism should be relatively rich in uranium, and because of their relatively high water content, might be especially likely to yield uranium-rich hydrothermal solutions. Some support for this suggestion is the fact that most of the world's important vein deposits of uranium and many uraniferous pegmatites are in ancient shields or massifs where rocks have probably been subjected to at least one episode of ultrametamorphism. The fact that few or no exploitable deposits of uranium have been found in other ancient shields and massifs may be a consequence of an originally inhomogeneous crust, but it is also possible that undiscovered deposits exist in favorable settings within these ancient terranes.

It seems likely that migration and perhaps concentration of uranium also may take place under less severe conditions of metamorphism. Marine black shales commonly contain appreciable quantities of syngenetic uranium, whereas



few graphitic slates have been reported to contain abnormal quantities, though several examples of epigenetic concentrations in or near such rock can be cited. In the Rum Jungle area of northern Australia, deposits of uraninite and secondary uranium minerals along with copper minerals occur in carbonaceous slates and graphitic schists; in Middle Asia, U.S.S.R., local concentrations of uraniferous turquoise, kolovratite, volborthite, and other secondary uranium-vanadium minerals occur in graphitic slate of Silurian age and in chert and carbonaceous shale of Cambrian age; in the Iron Ranges of the Great Lakes region, abnormal concentrations of uranium occur locally in graphitic schists and associated iron deposits of pre-Cambrian age. It seems quite probable that deposits of this type could be due to migration and local concentration of syngenetic uranium in black shale under conditions of moderate metamorphism rather than to introduction of uranium from an igneous source.

In summing up the concentration processes, it may be said that under the driving influence of orogenic forces, igneous processes tend to concentrate uranium in late-phase differentiates, notably in pegmatites, small alkalic plutons, and veins or other epigenetic deposits. The concentrations in igneous rocks are syngenetic, and though they may be large, they are almost invariably low-grade. Vein and other epigenetic deposits associated with igneous rocks are generally small, but some are high-grade. Weathering and sedimentary processes may either disperse or concentrate uranium, depending primarily on the climate. Some primary uranium-bearing minerals that are resistant to chemical and mechanical attack accumulate in placers. Other uranium-bearing minerals are dissolved, and the uranium is transported by ground and surface waters, from which, if climatic conditions are suitable, it may be precipitated in favorable receptors to form epigenetic deposits of a variety of types. Some uranium in solution reaches the sea from which it may be extracted to form large low-grade syngenetic accumulations in phosphorites or black shales. Metamorphic processes may yield concentrations of uranium either by converting pre-existing rocks to magma, which subsequently may yield uranium-rich differentiates, or by "sweating" uranium out of weakly uraniferous rocks and concentrating it in favorable geologic settings.

#### INFLUENCE OF OROGENY ON URANIUM CONCENTRATION

From the preceding discussion it is clear that uranium can be concentrated by various processes and in many geologic environments. The environments that exist and the processes that are active from time to time are largely determined by the orogenic history of a region. The world's important deposits of uranium, excluding low-grade deposits in phosphorite and black shale, are all in or adjacent to orogenic belts as might be expected, because magmas, the primary sources of uranium, are generated and emplaced or extruded in orogenic



belts. Though the histories of various orogenic belts differ in detail, all seem to evolve through four general stages:

1. The primary geosynclinal stage
2. The primary mountain-building stage
3. The secondary mountain-building stage
4. A stage of final differential uplift and local subsidence

In Stage 1, the primary geosynclinal stage, arcuate belts of subsidence form between major stable elements. Graywacke, argillite, chert, and submarine volcanic rocks, principally spilite, accumulate in the primary geosyncline, and shale and limestone, passing laterally in the direction of the stable block into first-cycle quartz sandstone, accumulate on the mobile shelf adjacent to the primary geosyncline. In Stage 2 the primary geosyncline is strongly deformed and intruded by synorogenic batholiths of intermediate composition, and secondary geosynclines are formed. In them accumulates the debris from the primary mountains, consisting mainly of graywacke and shale and locally of arkose and second-cycle quartz sandstone. In Stage 3 the geosynclinal belt is again strongly deformed; intermediate to acidic and alkalic plutons and volcanic rocks are emplaced and extruded; and continental sediments accumulate within and adjacent to the mountains. Highly differentiated small granitic and syenitic intrusives that may be rich in uranium are emplaced at or near the end of this stage, mainly in the secondary geosynclines and adjacent parts of the continental block but locally in the primary geosyncline. Stage 4 is characterized by block faulting and commonly by the extrusion of plateau basalt.

There is little likelihood that important concentrations of uranium form during the primary geosynclinal and primary mountain-building stages. The sediments accumulate too rapidly for syngenetic concentrations to form, and the magmas—mainly of simatic origin \* and ranging from ultrabasic to intermediate in composition—generally are not sufficiently differentiated to be important carriers of uranium. The lack of uranium deposits in primary geosynclinal belts and basic volcanic chains such as the Oregon-California coast ranges, the Philippine Islands, the Caribbean region, the Aleutian-Kamchatka arc, and much of eastern New England and the piedmont belt to the south attests to the general validity of this reasoning.

The optimum opportunity for concentration of uranium occurs during and following the secondary mountain-building stage. Uraniferous marine black shales and phosphorites may accumulate in the marginal parts of secondary geosynclines and on adjacent parts of the continental block. The highly differentiated granitic and syenitic intrusives that are emplaced during this stage

\* Referring to the second layer (inward) of the earth's crust, the *sim*a, rich in silicon and magnesium, on which the lighter and more acidic layer known as the *sial*, rich in silicon and aluminum, rests. [Ed.]



may be important bearers of uranium which may crystallize in the last-formed igneous rocks, or if structural conditions are favorable, in veins and other types of epigenetic deposits.

During the latter part of the stage of secondary mountain-building and the succeeding stage, which is characterized mainly by block faulting and locally by extrusion of plateau basalts, the earlier formed primary concentrations of uranium are attacked by weathering and erosive agencies, and if climatic conditions are favorable, a variety of types of secondary deposits may form. Uraniferous lignites and coals—most of them apparently formed by the leaching of acidic volcanic rocks by ground water—and placer deposits are noteworthy examples.

The enigmatic sandstone-type deposits, typified by those on the Colorado Plateau, also seem to be closely related to the latter part of Stage 3 in both time and space, though their origin is a subject of heated controversy. Most deposits of this type occur in predominantly nonmarine sequences that are the erosional debris of orogenic mountains and consist of interbedded, rather well-sorted sandstones and shales. It is not clear whether these deposits were formed by solution of uranium originally dispersed in the sedimentary prism, with subsequent transportation and redeposition in favorable traps, or by introduction of uranium from an igneous source; but an increasing volume of evidence seems to favor an igneous origin.

In the more ancient parts of the crust, particularly in pre-Cambrian shields and massifs, successive periods of deformation, intrusion, and metamorphism have provided opportunities for accentuation of original differences in the uranium content of the crust. Such areas are believed to be particularly favorable sites for uraniferous igneous rocks and uranium deposits of igneous or metamorphic origin.

#### APPLICATIONS OF THE PROVINCE CONCEPT TO PROSPECTING

Understanding the processes that concentrate uranium and being acquainted with the uranium province in the western United States, one infers that the only positive indicator of a province is the presence of a variety of types of abnormal concentrations, regardless of the amount of uranium concentrated in any particular deposit. However, the presence of a single epigenetic deposit in a geologically favorable area is sufficient to suggest that a province may exist, and if several deposits of a single type are known, the chance that other deposits will be found is very good. All the concentrations in a province may be of about the same age, but because of the high degree of mobility of uranium, deposits of more than one age are typical. The boundaries of uranium provinces are controlled by the interplay of many geologic and climatic factors and consequently are likely to be rather indefinite. These criteria for the recognition



of a province are perhaps obvious and undoubtedly incomplete. Almost certainly they will be sharpened as new discoveries are made and as the viewpoints of geologists change as a result of increased geologic and geochemical knowledge.

Where there is no information on the presence of uranium minerals or abnormally radioactive rocks, complex geology and the presence of acidic and alkalic igneous rocks (including small bodies of highly differentiated types) and mineralogically complex veins of base and precious metals may point to the favorability of an area for uranium.

The province concept is valuable in roughly appraising the potential of an area in which uranium deposits are known and in pointing out settings within a province in which exploitable concentrations might profitably be sought. If an area is known or suspected to be a province, every possible setting in which uranium might be localized should be investigated. These include acidic and alkalic igneous rocks and mineralized structures in the vicinity of such rocks; placers or sites where placers might occur; sequences of continental sandstone and shale, particularly those that contain abundant carbonaceous trash, admixed tuffaceous material, and petroleum residues or that are cut by small acidic or alkalic intrusives; lignite and coal, particularly if it is or was overlain by acidic volcanic rocks or is in a basin through which ground water from a granitic, arkosic, or acidic volcanic terrane drained; metamorphosed black shales; and conglomerate-bearing sequences deposited on a crystalline basement. More specifically, if abnormally radioactive igneous rocks and a few vein deposits have been discovered in a mountainous orogenic belt, one might expect to find more vein deposits in favorable structural settings—particularly in the vicinity of igneous rocks—and placers. In the less deformed erosional debris within and marginal to this belt, especially if the climate is arid or semi-arid, one should look for deposits of sandstone type, uraniferous lignite or coal, uraniferous petroleum residues, and perhaps placer deposits. If sandstone-type deposits have been found in a basin, one might profitably look for vein deposits in the adjacent mountains, provided that acidic igneous rocks and favorable structures are present.

The same principles apply to ancient shield areas where veins, uraniferous rocks, and placers are most likely to occur in the strongly deformed, metamorphosed, and intruded portions; uraniferous conglomerates may occur in peripheral and less strongly deformed, metamorphosed, and intruded rocks. Though uraniferous coal and petroleum residues are not to be expected, small deposits of uraniferous peat may occur locally.

As a corollary to the province concept, the writers would not expect to find more than a sporadic exploitable deposit in relatively recent eugeosynclinal \* belts or basic volcanic chains such as the California-Oregon coast ranges,

\* Characterized by rapid sinking accompanied by volcanic activity and intrusion of simatic rocks. [Ed.]



much of the Caribbean area, Hawaii, the Philippine Islands, the Aleutian chain, and Kamchatka and the Kuril Islands. Similarly, broad areas covered by rather thick sequences of relatively recent undeformed basaltic flows are relatively unfavorable, even though they may be surrounded and underlain by favorable geologic settings. However, where eugeosynclinal rocks and especially basic igneous rocks have been involved in later orogenies and intruded by acidic igneous rocks, they may assume a relatively high degree of favorability, for many vein deposits seem to favor basic igneous host rocks.

#### SELECTED REFERENCES FOR CHAPTER 4

- Bain, G. W., 1950: Geology of the fissionable materials. *Econ. Geol.* 45:273-323.
- Cady, W. M., 1950: Classification of geotectonic elements. *Trans. Am. Geophysics Union* 31:780-785.
- Cady, W. M., V. E. McKelvey, and F. G. Wells, 1950: Geotectonic relationships of mineral deposits. *Geol. Soc. Am. Bull.* 61:1447 [Abstract].
- Davidson, C. F., 1951: The distribution of radioactivity. *Min. Mag.* 85:329-40.
- 1953: The gold-uranium ores of the Witwatersrand. *Min. Mag.* 88:73-85.
- Davidson, C. F., and D. R. A. Ponsford, 1954: *On the Occurrence of Uranium in Coals*. London, Geological Survey and Museum, Atomic Energy Division, Report 147.
- Erickson, R. L., A. T. Myers, and C. A. Horr, 1954: Association of uranium and other metals with crude oils, asphalts, and petroliferous rocks. *Am. Assoc. Petrol. Geol. Bull.* 38:2200-2218.
- Faul, H. (Ed.), 1954: *Nuclear Geology*. New York, John Wiley & Sons, Inc.
- Finch, W. I., 1953: *Geologic Aspects of the Resource Appraisal of Uranium Deposits in Pre-Morrison Formation of the Colorado Plateau*. Oak Ridge, Tenn., U.S. Atomic Energy Commission TEIR-348, Technical Information Service.
- Fischer, R. P., 1942: Vanadium deposits of Colorado and Utah. *U.S. Geol. Survey Bull.* 936-P, pp. 363-394.
- Fischer, R. P., and L. S. Hilpert, 1952: Geology of the uravan mineral belt. *U.S. Geol. Survey Bull.* 988-A.
- Fleischer, M., 1953: Recent estimates of the abundances of the elements in the earth's crust. *U.S. Geol. Survey Circular* 285.
- Gott, G. B., D. G. Wyant, and E. P. Beroni, 1952: Uranium in black shales, lignites, and limestones in the United States. *U.S. Geol. Survey Circular* 220:31-35.
- Graton, L. C., 1930: Hydrothermal origin of the Rand gold deposits. *Econ. Geol.* 25: Supplement to No. 3.
- Hurley, P. M., 1950: Distribution of radioactivity in granites and relation to helium age measurements. *Geol. Soc. of Am. Bull.* 61:1-8.
- MacKay, R. A., and K. E. Beer, 1952: *The Albite-Riebeckite Granites of Nigeria*. London, Geological Survey and Museum, Atomic Energy Division Report 95.
- Mason, B., 1952: *Principles of Geochemistry*. New York, John Wiley & Sons, Inc.
- McKelvey, V. E., and J. M. Nelson, 1950: Characteristics of marine uranium-bearing sedimentary rocks. *Econ. Geol.* 45:35-53.
- Rankama, K., and Th. G. Sahama, 1950: *Geochemistry*. Chicago, University of Chicago Press.
- Stieff, L. R., T. W. Stern, and R. G. Milkey, 1953: *A Preliminary Determination of Age of Some Uranium Ores of the Colorado Plateaus by the Lead-Uranium Method*. U.S. Geological Survey Circular 271.



- Stugard, F., D. G. Wyant, and A. J. Gude, III, 1952: Secondary uranium deposits in the United States. *U.S. Geol. Survey Circular* 220:19-25.
- Tyurin, B. A., 1944: Karatauskoye mestorozhdeniye urano-vanidiyevykh rud [The Kara-Tau deposit of urano-vanadium ore]. Moscow-Leningrad, Akad. Nauk S.S.S.R., *Izvestiya, Seriya Geol. No. 2*, pp. 99-106.
- Weir, D. B., 1952: *Geologic Guides to Prospecting for Carnotite Deposits on the Colorado Plateau*. U.S. Geol. Survey Bull. 988-B.



## *Chapter 5*

---

### INFLUENCE OF REGIONAL STRUCTURE ON URANIUM OCCURRENCE IN THE WESTERN UNITED STATES \*

---

---

#### THE CORDILLERAN FORELAND

The Cordilleran Foreland is a region containing distinctive structural elements that forms a broad north-south belt parallel to and east of the Cordilleran geanticline (Fig. 5.1). The predominant geologic structure within the Foreland is a series of anticlinal mountains and broad asymmetric basins that contrast sharply with the folds and overthrusts related to the Cordilleran geanticline to the west. The mountains of the Foreland are bordered by flexures, and by high-angle normal and reverse faults. Many structures are covered by nearly flat-lying sedimentary rocks of Tertiary age. Most of the eastern margin of the Foreland is beneath the Tertiary rocks of the Great Plains and has not been defined.

The discovery of uranium deposits within the Foreland led to a study of where and why uranium is concentrated in this tectonic environment. Deposits of metallic minerals other than uranium minerals are few and widely scattered, and most are in outcrop areas of pre-Cambrian rocks. Uranium deposits, however, are widely distributed throughout the region as disseminated uranium and uraniferous lignites in the sedimentary rocks of the basins, and as veins in the crystalline cores of mountain ranges.

Structure contour maps showing the configuration of the top of the pre-Cambrian rocks are being compiled for a large part of the Cordilleran Foreland. Such maps, based on available geophysical or well-log data, enable one to project structures for considerable distances, even under a thick cover of nearly flat-lying Tertiary rocks. It is believed that use of the pre-Cambrian datum

\* The first four sections of this chapter, up to p. 90, are from Geneva Conference Paper 28, "Relation of Tectonic Elements in Pre-Cambrian Rocks to Uranium Deposits in the Cordilleran Foreland of the Western United States" by F. W. Osterwald of the U.S. Geological Survey. Selected references are listed alphabetically at the end of the chapter.



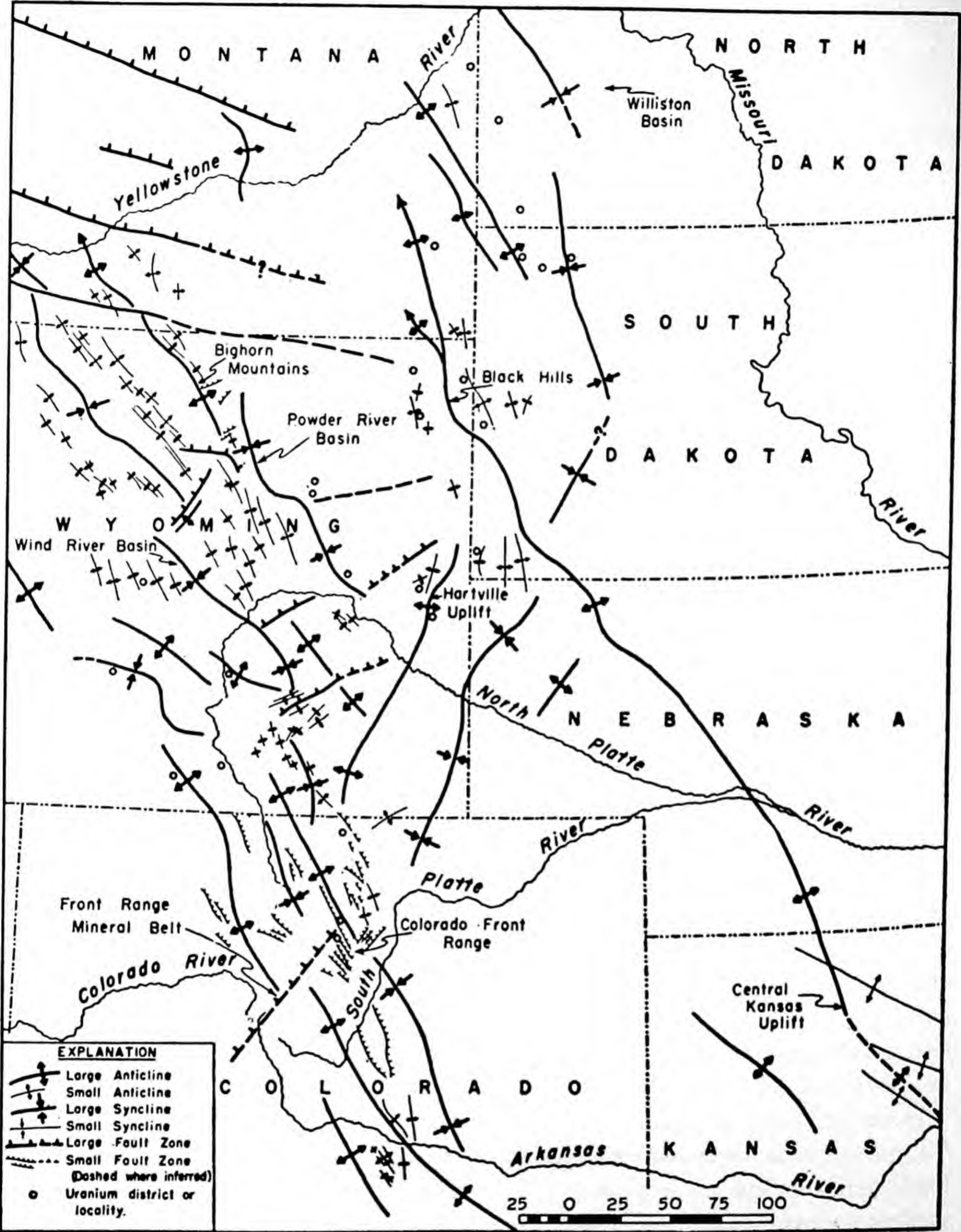


FIG. 5.1. Structural trends of the Cordilleran Foreland. Modified from Tectonic map of the U.S. Am. Assoc. Petroleum Geologists, 1944.



plane eliminates most of the effects of unconformities. In addition, structures of pre-Cambrian age undoubtedly have influenced the location and direction of later structures that are fundamental controls for localization of uranium districts. Therefore, by obtaining an accurate picture of the basement configuration beneath known uranium districts, one might pick out other areas of similar configuration.

#### INFLUENCE OF STRUCTURE ON LITHOLOGY

The lithology of some Mesozoic rocks of the Foreland exhibits a close relation to structure on both regional and local scales. The clastic material composing the rocks was derived, in large part, from the rising Cordilleran geanticline to the west; the result is a gradation from coarse-grained sediments to the west into finer-grained rocks to the east. Local uplifts probably influenced the sedimentation in their immediate areas by locally providing coarser-grained clastic material. Because some of these rocks provide favorable hosts for uranium deposition, the structural influence on lithology is important in the localization of uranium deposits. An example of regional influence is the Morrison formation of Jurassic age, which in the Foreland consists of siltstone and other argillaceous material with lenses of sandstone and fresh-water limestone, but which grades westward into sandstone. Though uranium minerals and radioactivity highs are widely scattered throughout the Morrison rocks in Wyoming, important uranium deposits are known only in the Colorado Plateau region, where sandstone is most abundant. Clastic rocks resulting from local uplifts provide favorable hosts for uranium deposits in the Black Hills.

The influence of local structures on lithology is illustrated best by some of the Lower Cretaceous sandstones in the southern part of the Powder River Basin, Wyoming (Fig. 5.2), which thicken near the axial parts of anticlines; the thickest part is slightly down structure from the crest of the anticline. The thickening is repeated in several stratigraphic units of different ages on the same structure, and deposition of the sandstones was influenced by repeated uplift of the growing structure. Similar thickening is probable on many anticlinal structures in the region. In the Black Hills the heavy-mineral suite of some sandstones of Lower Cretaceous age contains minerals similar to those found in pre-Cambrian rocks, suggesting that the sandstone formed during uplift of the Black Hills and that the pre-Cambrian rocks were being eroded at that time. Similar Cretaceous rocks contain commercial uranium deposits in this area. Because the lithology of the beds and the mineral suites, in these areas, were influenced by structures, it is believed that regional tectonics also were important in controlling the location of uranium districts by determining the location of favorable host rock.



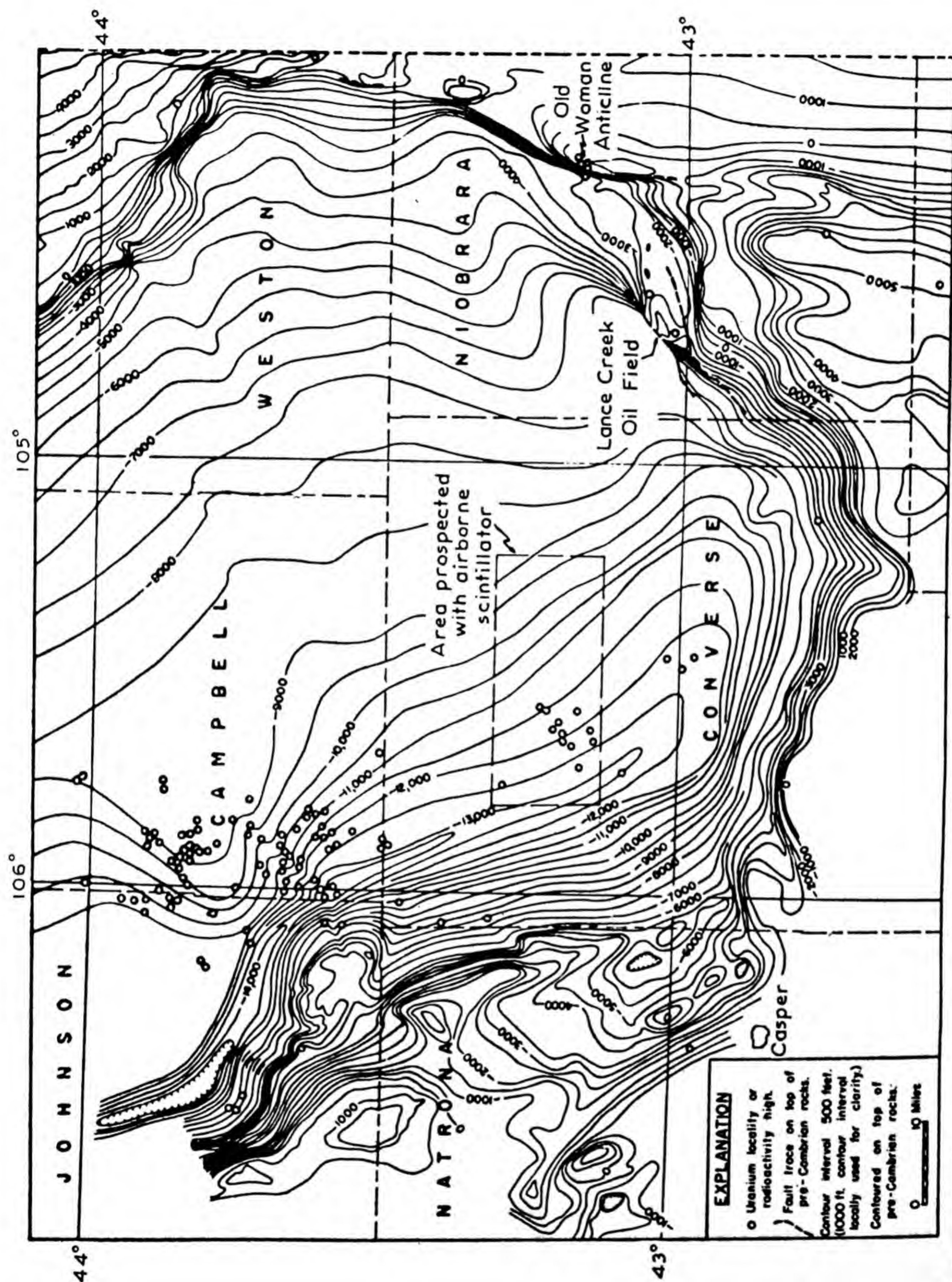


Fig. 5.2. Structure contour map of southern Powder River Basin, Wyoming. Compiled from all available sources.



Paleocene sediments in some basins of the Foreland are thickest in structural troughs, near and parallel to uplifts. Early Tertiary conglomerates at the edges of some basins in south-central Wyoming grade rapidly into shale and coal beds, as a result of abrupt changes in the tectonic conditions—rapidly rising mountains at the basin margins and more slowly subsiding basin centers. Stable areas bordering downwarped, unstable troughs, where rocks of dominantly medium-grained sediments are abundant, seem to be favorable localities for uranium deposition, as in the Williston Basin region (Fig. 5.1) and the Great Divide Basin, Wyoming.

Relatively young tuffaceous rocks crop out in some basin interiors, partly because the interiors suffer less erosion than the margins of the basins, and partly because thicker sedimentary sections are deposited in the basin troughs. As tuffs are possible source rocks of uranium, their presence in basins is favorable for the occurrence of ore deposits. Examples are small patches of tuffaceous sedimentary rocks of Oligocene age in the Powder River Basin (Fig. 5.1), which may have been source rocks for the uranium deposits in underlying rocks of Eocene age. Favorable beds in the underlying rocks, equally necessary for the localization of deposits, were probably controlled by the tectonic conditions during Eocene time. Regional unconformities beneath tuffaceous sediments probably controlled the movement of uranium; disseminated deposits and uraniumiferous lignites commonly are parallel to and beneath such unconformities.

#### TECTONIC ANALYSIS OF THE REGION

The various structures of the Foreland can be divided into three large classes to show the relation of uranium deposits to the structural pattern:

1. Large-scale structures include large mountain ranges, major basins, and fault zones with structural relief as much as a few tens of thousands of feet; some are several hundred miles long.
2. Intermediate-scale structures are large folds and faults superimposed on large-scale structures. These have a structural relief of a few hundred feet; few exceed several tens of miles in length.
3. Small-scale structures are folds, faults, and joints of lesser size which, though not important in the localization of uranium districts, nevertheless may be very important controls of individual deposits.

Large- and intermediate-scale structures within the Cordilleran Foreland are outlined on Figure 5.1. The three sets of large-scale structures, which trend northwest, northeast to north-northeast, and west-northwest, are of pre-Cambrian age. The northwest set is the most pronounced but is disrupted in part by the northeast set, which is probably younger. The west-northwest set appears only in central and southern Montana, and consists of long, almost



parallel faults or fault zones in pre-Cambrian rocks that apparently offset the northwest- and northeast-trending large-scale structures of pre-Cambrian age.

Most of the known uranium districts within the Foreland are in four structural environments: (1) areas near major basin axes along northwest-trending large-scale structures; (2) areas in which northwest- and northeast-trending large-scale structures intersect; (3) areas in which groups of *en echelon*, northwest-trending intermediate-scale structures are superimposed on northwest-trending large-scale structures; and (4) areas over or near large faults or fault zones in pre-Cambrian rocks, associated with northeast-trending large-scale structures.

Uranium districts near major basin axes are best illustrated by the Powder River Basin (Fig. 5.2), Williston Basin (Fig. 5.1), and Great Divide Basin of Wyoming. Most of the deposits in the Powder River Basin are located east of the basin axis, drawn on the pre-Cambrian surface. Many are located along a zone in which the slope of the surface increases. Most of the known deposits are at the north end of the group of deposits shown on Figure 5.2, where the basin floor is interrupted by a northeast-trending large-scale structure that has little or no surface expression. Little information is available concerning the northeast-trending structure, but it is probably a belt of fault blocks in pre-Cambrian rocks. Figure 5.2 also shows the outline of an area which was prospected with airborne scintillation counters. Anomalies and deposits were found only in the western end of the area near the basin axis; the eastern end is barren.

Uranium districts in areas of intersecting northwest- and northeast-trending large-scale structures include vein deposits in the Hartville Uplift (Fig. 5.1) and in the northern Laramie Range, Wyoming, and disseminated deposits in south-central Wyoming.

Uranium deposits in or near zones of *en echelon* intermediate-scale structures superimposed on northwest-trending large-scale structures include the vein deposits in the Colorado Front Range, the disseminated deposits in the Black Hills, and the disseminated deposits along the southwest margin of the Wind River Basin (all in Fig. 5.1).

Uranium districts over or near zones of large steep fractures associated with northeast-trending large-scale structures are illustrated by the deposits on the flank of Old Woman Anticline, Wyoming (middle right edge, Fig. 5.2).

#### LOCALIZATION OF URANIUM DISTRICTS BY TECTONIC ELEMENTS

The intersections of two major tectonic elements trending northwest and northeast, which seem to be favorable for localization of uranium districts, may be areas in which the energy levels were slightly raised by an increase in the geothermal gradient, by faulting and folding, or by a combination of the two



factors. The slight increase caused uranium, probably dispersed through the rocks as adsorbed or absorbed ions, to be expelled, moved, and later concentrated.

Margins of major tectonic units may be places in which the energy levels are changed by the same factors mentioned for intersections of elements, allowing uranium to be released and concentrated in smaller structures. However, the uranium probably would be merely moved upward and laterally and be redispersed in another place if favorable environments providing local points of low-energy level were not met. These environments are provided by structures such as the *en echelon* faults along the east margin of the Colorado Front Range (Fig. 5.1), and the anticlinal noses that localize deposits on the flanks of the Black Hills (Fig. 5.1). The ore is localized, however, not in the intermediate-scale structures, but in small-scale structures probably related to them. The uranium in the Front Range pitchblende vein deposits may have been dispersed originally in pre-Cambrian igneous and metamorphic rocks, and the uranium in the Black Hills disseminated deposits may have been dispersed in sedimentary rocks of younger age. The forces that expelled, mobilized, and concentrated the uranium in the two areas were probably similar and were probably active during Cretaceous or Tertiary time.

The repeated deformation along pre-Cambrian structural trends and the gradual, long-continued growth of structures may have caused nearly flat-lying Tertiary rocks to be slightly bent and jointed. Gentle folds and associated joints in Pliocene rocks in southern Wyoming indicate that at least some deformation took place late in Tertiary time. These minor structures in Tertiary rocks may have provided places of low-energy level to localize uranium mobilized by larger structures below. A possible example is the deposition in Tertiary rocks overlying the flanks of the Lance Creek oil field (Fig. 5.2).

Clusters of small plugs, dikes, necks, sills, and flows crop out in the Black Hills of South Dakota and Wyoming, in the Sweetwater arch of central Wyoming, and in the Leucite Hills of south-central Wyoming. Others that do not crop out are known from geophysical exploration. Most of the volcanic rocks are Tertiary in age, and some may have been the source for much of the pyroclastic material found in widespread sediments of Tertiary age. These alkaline volcanic clusters seem to be related to tectonic features in a manner very similar to that of the uranium deposits. The areas in which the energy levels were relatively high may have been raised locally even higher to permit small bodies of magma to form. Burbank pointed out that the formation of magma is a special case in which the energy level necessary for energy flow is so high that the flow results in a silicate liquid, and that previously mobilized elements may become mixed with material of the silicate melt. For these reasons, some of the bodies of igneous and pyroclastic rock may have provided uranium, which was later concentrated into deposits.



## INFLUENCE OF REGIONAL STRUCTURE IN THE COLORADO PLATEAU \*

The regional tectonic pattern has only little direct relationship to the distribution of uranium and related deposits in the Plateau (Fig. 5.3). However,

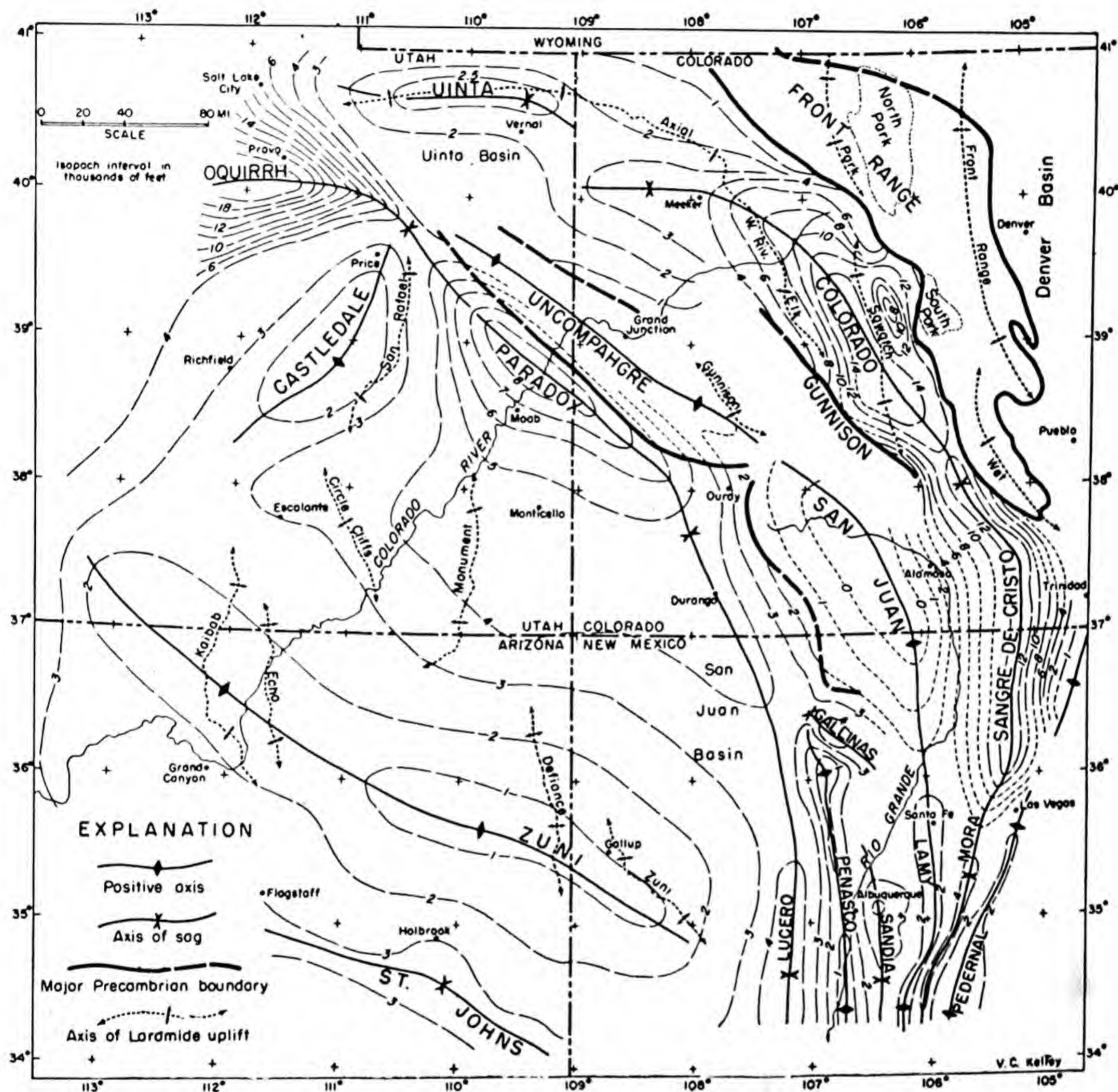


FIG. 5.3. Regional Tectonic Pattern of the Colorado Plateau.

indirectly the tectonic events of the past, probably as far back as Permian time, have had a most important bearing on the distribution of deposits through other geologic factors which may have contributed more directly to the distribution of ore. The principal factors of direct control are (1) provenances

\* From Geneva Conference Paper 29, "Influence of Regional Structure upon the Origin and Distribution of Uranium in the Colorado Plateau" by Vincent C. Kelley of the University of New Mexico.



and environments of sedimentation, (2) paleohydrology, (3) igneous activity, and (4) erosional history.

Although mineralization occurs in almost every formation of the stratigraphic section, the great preponderance of known commercial reserves and output of ore are from three relatively thin stratigraphic intervals within the Morrison, Chinle, and Shinarump formations.

In general, uranium occurrences fall into nearly every standard genetic type that has been proposed for mineral deposits. However, the great majority of deposits on the Plateau may be one or another of the following genetic types: (1) syngenetic, in sandstone, claystone, coal, tuff, (2) ground water, and (3) hydrothermal.

Most of the deposits have been oxidized or modified to some extent by ground water. In some instances this may have involved only chemical rearrangement *in situ* or migration and concentration a few feet or a few tens of feet away. Elsewhere leaching from up-dip or near-surface outcrops or from overlying beds may have been effective in ore concentration. It is also considered possible that ground water may have brought the ore from considerable distance.

There are few deposits on the Plateau that are unquestionably hydrothermal by reason of being on fissures or connected directly to mineralized fissures. Yet in spite of this there remains the possibility that every deposit on the Plateau is indirectly of hydrothermal origin. This possibility is unlikely to be disproved so long as conclusive evidence of a syngenetic origin is lacking.

Past hydrologic conditions are one of the most important of the problems controlling origin and distribution of ore on the Plateau. As with the present, the principal controls for the ancient hydrology are structure, geomorphology, and climate.

Radioactive age determinations indicate a Laramide age for Plateau uranium ores. However, because these determinations may not be entirely conclusive and because ground water might have concentrated ore earlier, only to be reworked and redeposited during Laramide time, the earlier hydrodynamics should be considered.

During Shinarump time hydrodynamic conditions were very favorable for concentration of ore in the channel bottoms owing to the unconfined occurrence of the water. With the widespread and commonly deep burial by the Chinle and Jurassic sandstone formations, Shinarump hydrodynamics may have changed significantly. Recharge would have diminished because of overlap of the Shinarump, aridity, and deep burial. Furthermore, in the middle part of the Plateau the Shinarump may have been unwatered and some unconfined "puddling" in channels and other low areas may have occurred.

During Morrison time, marked fluvial and lacustrine conditions, probably indicating at least moderate surface-water supplies, returned to the Plateau. The highland areas were principally along the southern rim and to the west



of the present Plateau, although some lesser highlands probably existed in parts of the present Eastern Rockies of Colorado. Surface and ground-water flow may have discharged to great playas and lakes at various places in the east-central part of the Plateau.

The gentle warping that may have gone on during Morrison time was accentuated in late Jurassic and early Cretaceous times. Along the southern rim of the Plateau erosion truncated successively older beds southward. Surface recharge of all the exposed permeable units must have been widespread. Uranium derived from the eroding outcrops could have been introduced into the Shinarump and Morrison beds at this time. Furthermore, since much volcanic activity took place to the south, as is shown by the composition of the thick early Cretaceous rocks of southern New Mexico, hydrothermal additions to the early Cretaceous ground-water system of the Plateau region could have been made.

Throughout most of Triassic and Jurassic times ground-water flow in the central part of the Plateau was generally northwesterly toward a discharge area along the Cordilleran geosyncline.

During late Cretaceous time the entire Plateau subsided greatly as a part of the Rocky Mountain geosyncline. The Cordilleran geanticline west and southwest of the Plateau rose continuously and furnished sediment together with abundant supplies of water. By middle Cretaceous time the magnitude of the uplifts in the Central Rockies may have been sufficiently great to reverse the direction of subsurface flow in formations of the western part of the Plateau. Toward the end of late Cretaceous deposition the Shinarump and Morrison formations of the San Rafael Swell and Henry Mountains areas were buried and probably below sea level by 10,000 and 7000 feet respectively. Similar deep burial of the principal ore-bearing intervals existed over most of the rest of the Plateau. Temperature in the ground water at these depths may have been about 150°F. In order for eastward flow in the ore-bearing formations to have occurred there would have to be an upward escape of ground water through the overlying units by slow mass permeation and movement along fissures to the surface, especially in the low areas near sea level. Theoretically at least, ground water would flow no farther east than the coast line of the marine sea. Beneath this sea it is likely that all the ground water would be stagnant and saline. The dense saline water would form a steep barrier across the formations, blocking eastward flow of fresh water from the source areas. As the late Cretaceous shore line fluctuated slowly east and west across a low-gradient surface, so would the subsurface interface between fresh and saline water. It is interesting and perhaps significant to note that the areal band, in which fluctuation of the interface between fresh and salt water occurred, includes most of the large ore bodies on the Plateau. In this area, ground water in the Morrison and Shinarump may have been 120°–170°F. It was very slowly



"surging" east and west with the shoreline above, and changing repeatedly from fresh to saline. The effect this may have had upon ore concentration is primarily a problem of geochemistry. Within the band of the fluctuating interface the pH and other chemical features of the ground water probably would be changed repeatedly.

The comparatively simple tectonic and hydrologic conditions that prevailed on the Plateau during most of late Cretaceous time were changed greatly with the onset of the Laramide deformation of the Plateau and adjoining areas in late Montanan, Lance, and Paleocene times. Deformation, uplift, and erosion in the Central Rockies continued to provide recharge of the aquifers and a hydrostatic gradient eastward in the western part of the Plateau. New sources of water and hydrostatic head developed in the Uinta uplift, Eastern Rockies, and probably also along the southern rim of the Plateau as it was given a broad general tilt northward. In the early stages while Cretaceous rocks still blanketed the uplifts, changes in the hydrodynamics of the Morrison and Shinarump would have been slight. Gradually, however, and even before complete removal of the thick Cretaceous some recharge in these newly uplifted areas probably would have occurred. This would have first stopped the eastward ground-water flow and then reversed it along the eastern and southern sides. The Uinta uplift diverted the flow southward. The earliest effect of the orogenies would have been to concentrate the flow inward toward the central part of the Plateau, probably in a north-northwesterly trending ground-water basin centering around the Blanding Basin. Some of the relatively dense connate sea water would have been pushed into deep basins such as the Uinta, Piceance, and San Juan, where it may have remained a longer time or even to the present. Much salt-water flushing may have been accomplished by Paleocene times.

As erosion and truncation proceeded in the uplifts around and within the Plateau, successively older formations would have been exposed to recharge, thereby rejuvenating the ground-water flow. Wherever this occurred, reversal of direction of former ground-water flow on one side of the uplift took place.

It may be observed from the above descriptions that the paleohydrology of the Plateau is complicated and that fluids in the principal ore-bearing units have moved in numerous different directions and with differing flow potentials in the various uplifts, basins, and other structural divisions of the Plateau (Figs. 5.4, 5.5). Temperatures rose, with burial, to those of epithermal conditions during the time when the primary ores formed and then declined slowly with unloading and exposure in outcrop. Salinity and probably the pH of the fluids may have changed many times in the central Plateau, as salt water and fresh water alternately replaced one another while the areal distribution of the late Cretaceous seaway expanded and contracted.

Although tectonic controls on the distribution of hydrothermal activity are implied from discussions above, certain special aspects related in particular







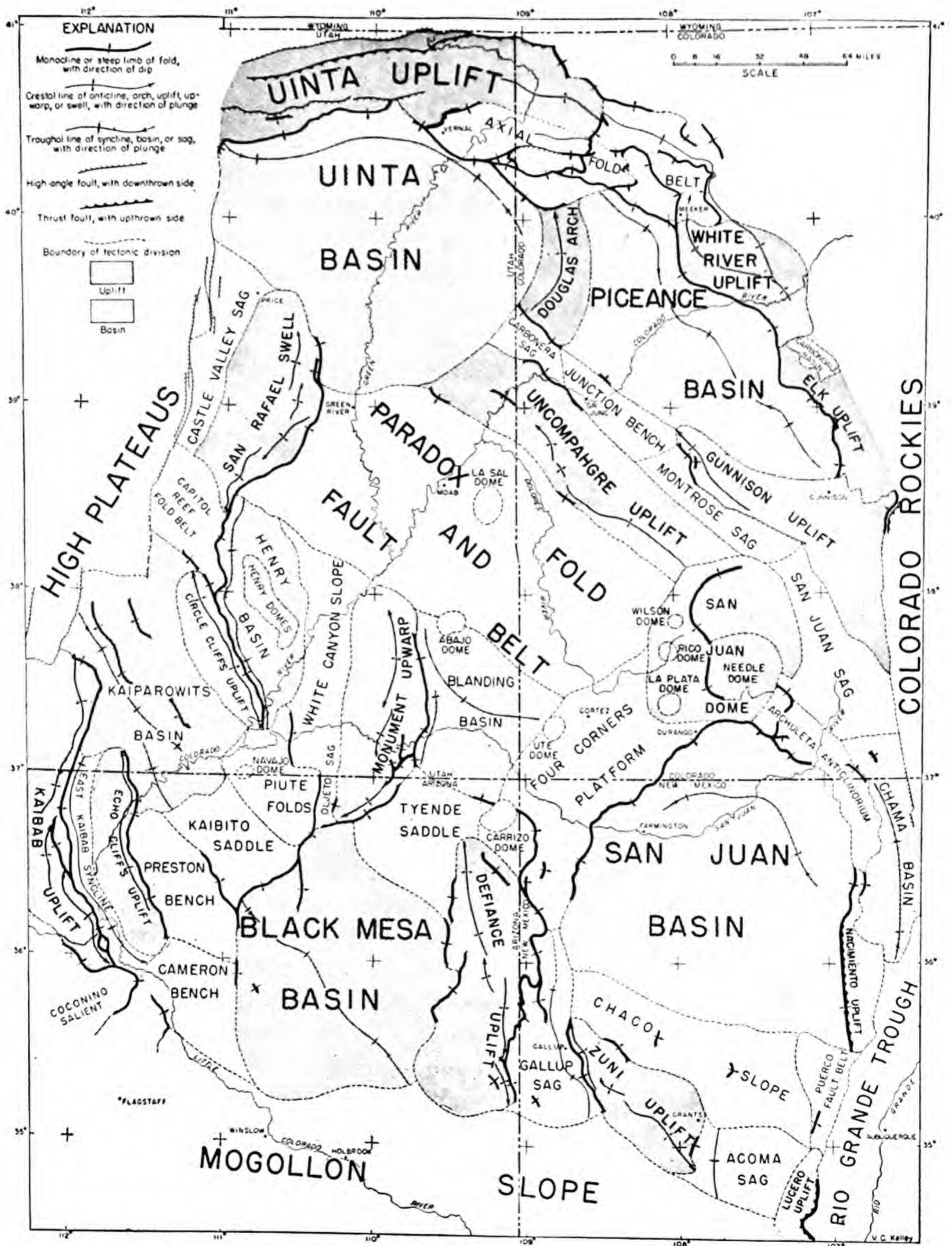


FIG. 5.5. Structural divisions of the Colorado Plateau.



to the hydrodynamics will be discussed further. A great deal of hydrothermal action very likely occurred in source areas of the Chinle and Morrison formations. Furthermore, the great amount of fine volcanic material in several of the late Cretaceous formations suggests the possibility of hydrothermal activity during that time to the west and along the southwestern side of the Plateau. Hydrothermal fluids coming into the epithermal zone become considerably diluted by ground water, and the introduced metals may be moved far and remain in the meteoritic system for long periods. Thus, uranium introduced by hydrothermal fluids during Chinle or Morrison times may have stayed in solution until the period of falling temperature which ensued with Laramide erosion.

It is abundantly clear from field relations that a great deal of hydrothermal activity occurred on the Plateau during Laramide and succeeding times. Alteration in and around the porphyry stocks and laccoliths suggests that a considerable volume of hydrothermal fluid was introduced into the ground water of the surrounding area.

With the emplacement of a porphyry center, there is established an outward radial flow potential in the associated ground water that is of two derivations. With intrusion and crystallization a vapor pressure center is built up and superimposed upon the pre-existing ground-water gradient. At the same time or after this pressure subsides, a radial flow potential is maintained by reason of the structural high and high ground, from which meteoritic ground-water penetrations will radiate. The tectonic modifications of the ground-water flow by the Uncompahgre, San Juan, and Monument uplifts probably caused a flow to concentrate along the Utah-Colorado line. Also the La Sal, La Plata, Abajo, and Ute centers would further accentuate the flow in this area. In general the uplifts, the flow directions, and hydrothermal sources highly favor areas amongst such intrusive centers, and this is where most of the uranium of the central Plateau occurs. Greater concentration of ore is found nearer to the La Sal center than to others, perhaps because ground-water flow, lithology, and local structural channels (salt piercements) were more favorable, together with a greater release of uranium from the La Sal center.

Hydrothermal introductions into the ore-bearing formations may have been made through (1) surface flow, (2) lineal flow from fissures, (3) pipelike conduits of diatremes and fissure intersections, and (4) wide-area pervasions. In general, "pin-point" or pipelike feeding of ore beds by hydrothermal fluids is probably the most common entry. This, of course, is much more difficult to detect on the surface, and conduits may not crop out. Underground mining likewise does not ordinarily reveal them, especially if they only enter the bed from below and do not transect it.

If there is relatively strong meteoric flow along a bed and past a point of only mildly disturbing hydrothermal entry, then the hydrothermal material may be



swept in a path along the direction of flow in the bed. If the hydrothermal entry was lineal and not parallel to the ground-water flow lines, a wide band of hydrothermal contamination would result. A lineal entry parallel to the direction of meteoric flow would produce a streak or narrow band of hydrothermal contamination. Streaks of ore-bearing hydrothermal fluid in an otherwise barren ground-water system might not encounter many favorable sedimentary channels, organic debris, or favorable minor structural traps.

Another variable that may operate during hydrothermal introductions arises from the possibility that the hydrothermal fluid is sufficiently denser than the meteoric water to maintain a gravity separation between the two within a permeable layer. If a dense hydrothermal fluid enters a bed at its base and remains unmixed, it may underflow the lighter fluid either up dip or down dip. Under these conditions the heavy ore-bearing fluid might accumulate in stagnant pockets near the bottoms of channels, synclines, or the downthrown side of faults. Thus with east-to-west flow the lower west sides of certain north-trending channels or troughs and the bases of small faults downthrown on the east would "puddle" the heavy solution under favorable relationships of dip and flow potentials, and result in concentration of ore.

In summary, an indirect tectonic control may be deduced for any of the commonly postulated origins of uranium. Syngenetic deposits as well as favorable rock compositions, which may precipitate ore from solution, are reflections in part of the tectonics of the time. The principal problem within the tectonic control is the history of the circulation of ground water. This is influenced or controlled by past climate and geomorphology as well as the structure. Repeated changes in direction of ground-water flow have resulted from orogenic and intrusive tectonics.

There is no doubting the fact that hydrothermal emanations have been added to the ground-water system of the Plateau. There have been several periods of such additions since the Triassic. They may or may not have brought in much of the ore, but the introduction of fluids regardless of uranium content during Laramide time probably considerably modified the ground-water flow potentials. Hydrothermal contamination of the meteoric ground-water systems was most commonly centralized in its entry and linear in its movements, and expansive spreading of hydrothermal introductions in Shinarump or Morrison sandstone beds probably occurred only rarely.

A general consideration of the paleohydrodynamics of ground water in the Plateau makes the greater concentration of ore in the area amongst the several uplifts and igneous domes appear logical.

#### SELECTED REFERENCES FOR CHAPTER 5

- Blackstone, D. L., Jr., 1953: Tectonic map of southern Wyoming and northern Colorado. Wyoming Geol. Assoc., 8th Annual Field Conf., *Guidebook*.



- Kelley, V. C., 1955: *Regional Tectonics of the Colorado Plateau and Relationship to Origin and Distribution of Uranium*. University of New Mexico Publications in Geology No. 5.
- King, P. B., 1951: *The Tectonics of Middle North America East of the Cordilleran System*. Princeton, N. J., Princeton University Press.
- Love, J. D., 1952: *Preliminary Report on Uranium Deposits in the Pumpkin Buttes Area, Powder River Basin, Wyoming*. U.S. Geological Survey Circular 176.
- 1953: *Preliminary Report on the Uranium Deposits in the Miller Hill Area, Carbon County, Wyoming*. U.S. Geological Survey Circular 278.
- Lovering, T. S., and E. N. Goddard, 1950: *Geology and Ore Deposits of the Front Range, Colorado*. U.S. Geological Survey, Professional Paper 223.
- Osterwald, F. W., 1956. Structure and Petrology in the Northern Bighorn Mountains, Wyoming. *Geol. Survey of Wyoming Bull.* (in press).



## *Part Two*

---

TECHNIQUES OF PROSPECTING  
FOR URANIUM AND THORIUM







## Chapter 6

---

### INTRODUCTION: SURVEY OF PROSPECTING TECHNIQUES

---

\* The high degree of past success achieved in uranium exploration has been due largely to two factors: the importance attached to it, which has telescoped a century of normal exploration progress into one decade; and the natural radioactivity of uranium minerals. The latter is shared by thorium, and should its importance reach that of uranium, similar results may be expected.

† In no phase of mineral exploration is there a wider range of technical methods at the disposal of the prospector than in the search for radioactive ores. Indeed, so many are the techniques available, and so vociferous are their respective advocates, that it tends to be forgotten that successful prospecting is almost always based upon the application of fundamental geological knowledge. Nearly all important deposits of uranium and thorium have been found, not by chance, but by the systematic exploration of country which geological experience suggested was potentially hospitable to radioactive mineralization. It is true that, very exceptionally, wild-cat discoveries have been made by enthusiastic amateurs equipped with Geiger counters, and the operations of workers of this kind deserve every encouragement. But in any major program of mineral exploration, useful discoveries are most likely to be made where the field work is founded on sound scientific knowledge. Geological control is a prerequisite to all intelligent prospecting operations, no matter what ancillary aids to exploration are employed.

The first essential step towards making a systematic exploration for radioactive mineralization in any circumscribed region is therefore a comprehensive study of the existing geological information on the area in question by one or more geologists who are well acquainted with the now extensive literature

\* Oral summary of Geneva Conference Paper 503, "Techniques of Prospecting for Uranium and Thorium" by staffs of the U.S. Geological Survey and Division of Raw Materials, U.S. Atomic Energy Commission, presented at Geneva by Robert D. Nininger, U.S. Atomic Energy Commission.

† From Geneva Conference Paper 764, "Methods of Prospecting for Uranium and Thorium" by C. F. Davidson and S. H. U. Bowie, Geological Survey of Great Britain.



describing the geological, geochemical, and structural environments in which such mineralization is most likely to occur. From such preliminary research it may in many instances be possible to postulate what are potentially the most favorable localities demanding priority in field operations. All known occurrences of mineralization, particularly sulfide mineralization, should be systematically listed, for more uranium ore has been found in old prospects and in working or derelict mines than anywhere else; and attention should be specifically directed to formations which bear an apparent petrological similarity to known uranium provinces elsewhere. Contemporaneously with this work, the prospectors to be engaged in the field operations should receive training in the recognition of common radioactive minerals—not only of the fine specimens found in museums, but more particularly of the paintlike traces of secondary uranium minerals and of the iron-rich gossans without visible uranium which so often are all that is seen at the surface. The type of training given must differ greatly according to the terrain to be explored—that appropriate to the glaciated lands of Canada, for example, being entirely dissimilar to that necessary for successful work in the heavily weathered and soil-masked rocks of Central Africa. In this preliminary phase also the mineral scout should be instructed in the use and maintenance of the instrumental aids with which he may be supplied, such as ratemeters for routine prospecting and for field assay work, and ultraviolet lamps for fluorescence tests. In all radioactivity explorations the principal tool of the intelligent prospector, surpassed in importance only by his geological knowledge, is a field ratemeter, either a Geiger-Müller or scintillation counter.

\* Prospecting with radiation detection equipment has been carried out extensively in the United States since 1944. Geiger and scintillation counters and ionization chambers are now used routinely in surface, subsurface, and aerial exploration. The development of small-diameter scintillation and Geiger drill-hole probes and light, highly sensitive scintillation counters for aerial use has perhaps been the most significant advance in this field.

In the future successful prospecting for radioactive minerals will require increased attention to the geologic, geochemical, geophysical, and engineering techniques on which exploration for other metals has had to rely.

#### GEOLOGIC TECHNIQUES \*

The use of the rapidly expanding knowledge of uranium and thorium geology to define potential metallogenic provinces and to predict local favorability for deposits is greatly increasing the rate of discovery of new mineralized areas and of new ore deposits within producing areas. Although important deposits have

\* Geneva Conference Paper 503.



been found in environments which at one time were not believed to be favorable, virgin areas can often be evaluated in advance, with some degree of assurance, on the basis of present knowledge.

Frosppecting for epigenetic deposits of uranium, whether of direct or indirect magmatic origin, should emphasize areas of deep-seated major structures, particularly those related to (1) near-surface intrusions, (2) basins containing terrestrial sediments, (3) areas of metamorphosed clastic sediments, and (4) granitic batholiths. Syngenetic deposits should be sought in (1) marine black shales and phosphorites, (2) terrestrial and marine placers, (3) alkaline igneous stocks, sills, and dikes, and (4) granitic pegmatites.

Epigenetic deposits of thorium commonly occur in areas of metamorphic and igneous rocks associated with syenitic intrusions; syngenetic deposits are found in such rocks and in placers derived from them.

Within favorable terranes, specific stratigraphic zones; lithologic, mineralogic, and structural characteristics; and alteration phenomena, all of which are amenable to mapping, are the most important guides to ore. Directional sedimentary features of paleostream flow often control in detail the occurrence of uranium ore bodies in sandstones. Maps of such features as cross-bedding, lineation on bedding planes, logs, channels, scours, and ripple marks are aids to exploration.

Around the Black Hills of South Dakota the sandstone host rock is capped by impermeable beds. Structure contour maps on the upper surface of the porous sandstone have delimited favorable structures, such as anticlines, terraces, and zones of lithologic interfingering, that have apparently controlled ore deposition.

Mapping of the ratio of mudstone to sandstone and of the degree of color favorability in the Jurassic Saltwash formation proved useful in a drilling project in the Lukachukai Mountains of the Colorado Plateau. Unusual thickening of the Shinarump conglomerate, or bleaching of the immediately underlying Moenkopi beds from dark red to light gray-yellow, indicates the presence of channels and the possibility of mineralization. Maps of the lower surface of the host rock define the channels and the more favorable places for ore deposition.

Iso-abundance maps of specified grain sizes, diagnostic heavy minerals, base metals, and lithologic types have also been used as guides. Contour maps of the water table, indicating the abundance of critical elements such as fluorine in the water, are helpful in areas of caliche-type mineralization such as the shroeckingerite deposits of the Red Desert region, Wyoming.

Mapping of clay mineral and hematitic alteration zones in proximity to veins in igneous and metamorphic rocks, as at Marysvale, Utah, or associated with collapse features in sandstones, as at Temple Mountain, Utah, has proved useful.



## GEOCHEMICAL TECHNIQUES

Geochemical prospecting techniques are rapidly being adapted to uranium exploration, and may prove useful in the search for thorium. Relatively simple and inexpensive but rapid and sensitive field techniques can detect uranium anomalies directly, by chemical methods. Significant uranium concentrations in areas of sedimentary rocks may be as low as 1 part per million or 5 to 10 times background. Anomalous concentrations of vanadium, molybdenum, selenium, zinc, copper, cobalt, and niobium may also indicate uranium.

The uranium and radon content of surface and ground waters may serve as an approximate index of the uranium concentration in the rocks with which the water has been in contact, depending upon variables of water pH, temperature and composition and rock composition and permeability. Background for major streams in the United States is commonly about one-tenth part per billion ( $10^{-10}$ ) of uranium. The threshold of significance is 3 to 10 times background.

In the Colorado Plateau area the threshold of significance is about 4 parts per billion with a content of 5 to 12 parts per billion in uraniferous areas. Ground water is usually much higher in uranium content: about 1 to 10 parts per billion in barren aquifers and 5 to several hundred parts per billion in mineralized aquifers.

Water seeps and springs in the Black Hills area of South Dakota and Wyoming contain 10 to 250 parts per billion of uranium in mineralized areas and have led to the discovery of ore deposits in locations not otherwise thought to be favorable.

Geobotanical prospecting has shown that uranium deposits under as much as 20 meters' cover may be reflected chemically in surface vegetation. In semi-arid country, trees or deep-rooted shrubs that are absorbers of uranium show differences in uranium content which may indicate the presence or absence of ore. The uranium content of the ash of plants growing in unmineralized sandstone is generally less than 1 part per million; a content of several parts per million is common in the ash of plants rooted over ore.

Sampling of indicator plants has also been used. Carnotite and other oxidized uranium ores contain appreciable amounts of selenium and sulfur. The distribution patterns of plants requiring one of these elements in quantity may indicate favorable ground.

## GEOPHYSICAL TECHNIQUES

Uranium deposits have not proved susceptible to direct detection by geophysical means. Some geophysical methods have proved to be of great value, however, in the detection and delimitation of geologic features which localize ore, even though in some cases these features may be obscure.



There is no recognizable difference in electrical resistivity of sedimentary formations attributable directly to uranium minerals that may be present. However, resistivity highs have been found associated with carnotite-type mineralization in South Dakota, and low resistivity has indicated uranium carbonate and phosphate-type mineralization in Wyoming.

Formational irregularities such as paleochannels have been successfully located by continuous profiling with reversed shots, using standard seismic refraction equipment. The shallow reflection method, using continuous velocity logging in conjunction with high-resolution seismic equipment, also offers promise. Channels have also been located by a combination of vertical and horizontal resistivity profiling.

The routine use of electric logging, in conjunction with gamma-ray logging, on drilling projects has substantially improved subsurface lithologic information. Formation resistivities can be determined with accuracy by using single-point, in-hole equipment. A new type of electrode which provides a rolling, wet contact with the dry rock has been developed for logging dry holes.

#### ENGINEERING TECHNIQUES

Lastly, as a result of the unprecedented scale of uranium exploration activity in the United States and the very large requirements for subsurface information, great advances in drilling techniques have been made. Several types of drilling equipment are used. All equipment is mobile—jeep or truck-mounted.

The standard mining diamond drill is the most versatile and gives the greatest amount of information, providing rock cores as required. It is also the slowest and most expensive method used, although drilling rates up to 30 meters per 8-hour shift have been achieved in shallow holes.

The operating cost of larger-diameter, noncore oilwell drilling equipment is  $\frac{1}{2}$  to  $\frac{1}{6}$  that of the standard diamond drill, and it is three to eight times more rapid. Rates up to 400 meters per 8-hour shift have been attained. Samples of sludges or cuttings may be collected, but radiometric and electric logging of holes provides more reliable information.

Percussion air-drilling is a rapid, economical method feasible at depths up to 75 meters in dry rock. Samples are collected as in dry rotary drilling, and the information is confirmed by radiometric and electric logging. Cost and speed are equivalent to rotary drilling but the cost of the equipment is much less.

#### GENERAL EXPERIENCE IN CANADA \*

**Types and distribution of known deposits.** The types and modes of occurrence of known deposits both in our own and in other countries has an important

\*From Geneva Conference Paper 1, "Uranium Prospecting in Canada—Ground and Aerial Surveys" by A. H. Lang, Geological Survey of Canada.



bearing on the selection of areas for prospecting and on the geological formations, structures, and mineral associations that warrant attention. It is important to bear in mind, however, that other unsuspected areas and conditions may also be fruitful. A wide variety of uranium deposits have been found in Canada, but those that are producing or for which production is assured at the time of writing are "hydrothermal" pitchblende deposits occurring both as veins and as disseminations, and uranium-bearing conglomerate whose origin is still open to more than one interpretation. The origin of the latter may have an important bearing on prospecting for other deposits of this kind. Pegmatites and related types of deposits containing uranium minerals, generally in minor amounts, are very common. Most appear to be unfavorable, but it has always been pointed out that there might be exceptions, and we now have a few that are showing promise.

By far the majority of known occurrences, and all the present producers and assured future producers at the time of writing, are in the Canadian Shield. About fifty occurrences are known in the Cordilleran region, and some are promising. A few occurrences have been found in the Appalachian region, but so far have warranted only limited exploration. Discoveries have not yet been made in the Plains or Innuitian \* regions. Most of the discoveries in the Shield are in a wide marginal belt, and the "hydrothermal" and "conglomerate" deposits show a tendency to occur in rocks of late pre-Cambrian age and in older rocks that have been subjected to folding and faulting in late pre-Cambrian time. There are some geological foundations for these generalizations, but also the distribution of known occurrences is partly related to the accessibility of the marginal belt. Therefore other parts of the Shield and regions outside the Shield have possibilities.

**Ground methods of prospecting.** The principles of choosing areas for prospecting, and the basic techniques of prospecting, are applicable to uranium and to other metals. They include paying attention to favorable rocks and geological structures, wall-rock alteration, mineral associations, and brightly colored secondary minerals. They also include the tracing of mineralized fragments to their source and the use of the prospector's pan. A highly specialized phase consists of diamond-drilling along particularly favorable geological contacts or structures even when no indication of the mineral sought has been found at the surface.

Basically, there are two methods of covering terrain. The *roving method* consists of a day's travel more or less at random, usually on foot. The *systematic method* consists of fairly or completely systematic traverses, usually guided by plotting points on air photographs or by pace and compass traverses or picket lines, in much the same fashion as in the making of a geological map. The lines may be from  $\frac{1}{2}$  mile to 100 feet apart, depending on the size of the

\* Arctic. [Ed.]



area to be covered and the detail required. Both methods are useful and depend much on conditions. The roving method is more usual for reconnaissance and the systematic for detailed work in smaller areas, but the systematic method is also used for preliminary work in large areas, particularly when a number of relatively unskilled men are employed under supervision.

**Judging and exploring discoveries.** The main principles of judging and exploring are the same as for mineral deposits in general. In brief, they constitute a system of elimination by which many discoveries are classed as not appearing to warrant any attention, and others as meriting preliminary exploration; increasingly large expenditures are risked on diminishing numbers of prospects, following successive reappraisals. It is far from being a perfect system because of the number of unknown or uncertain factors. Delays and mistakes are inevitable, and there is an element of luck as well as scope for the highest engineering and scientific skill and experience. It seems, however, to be the only system on which the mining industry can be based.

First is the question of the ratio of discoveries to producing mines. It is well known to persons experienced in prospecting and mining that most mineral occurrences cannot be classed even as prospects, and that only a few prospects eventually become producers. The ratio is probably even more unfavorable in the case of radioactive minerals because many of them occur as accessory minerals in intrusive rocks and in other sparsely distributed ways, and because the use of counters permits the detection of small or low-grade mineral occurrences that might otherwise be unnoticed.

The question of the amount of reliance that should be placed on samples from altered surface showings is a difficult one for which there is not yet a definite answer. The history of the Pronto property in the Blind River region of Ontario suggests that it may be a serious problem in connection with some kinds of deposits. In general, the practice is to risk preliminary drilling if the structural conditions, width, length, and other factors are favorable, even if assays from altered surface showings are low.



# Chapter 7

---

## GEOLOGIC PROSPECTING

---

---

### INTRODUCTION \*

All known characteristics of uranium and thorium deposits must be used to make geologic prospecting successful, and because our knowledge changes from day to day, good prospecting is the result of theories based on continuously changing hypotheses. Although there are only two main groups of deposits that are sought—epigenetic and syngenetic—there are many theories to explain the origin and localization of each deposit.

The search for epigenetic and syngenetic deposits can be narrowed down to specific types of terrane that have little or no relation to stratigraphic or geologic timetables, but rather are related to the depth of erosion and to major magmatic, sedimentary, or tectonic environments. In the United States epigenetic deposits of ore grade are most abundant in (1) areas of deep-seated tectonic structures, particularly those related to small, near-surface intrusive and associated extrusive rocks of alkalic affinities, (2) depositional basins containing terrestrial sediments, particularly sandstones, and (3) deeply eroded granitic batholiths. The syngenetic deposits, mostly below ore grade, are limited to areas of (1) granitic igneous rocks, (2) continental shelf organic- or phosphatic-rich sediments, (3) placers derived from granitic batholiths and high-grade metamorphic rocks, and (4) terrestrial and near-shore marine sediments. Areas of ultramafic † rocks and plateau basalts, as well as marine sandstones and limestones, have as yet yielded little radioactive material.

If we assume an ultimate magmatic source of uranium or thorium (or both) for each of the terranes mentioned, different structural, lithologic, and chemical environments delimit the distribution of ground favorable for the occurrence of uranium or thorium regions or districts and within this favorable ground determine the localization of ore deposits.

\* From Geneva Conference Paper 504, "Geologic Prospecting for Uranium and Thorium" by L. R. Page, U.S. Geological Survey. Selected references are listed alphabetically at the end of the chapter.

† Composed largely of ferromagnesian minerals rather than feldspars and quartz. [Ed.]



**Guides to major areas.** The localization of uranium and thorium regions within the earth's crust is the result of the interplay of complex geologic processes that tend to concentrate these metals in particular petrographic and metallogenic provinces. The search for new major ore regions is therefore fundamentally one of applying our knowledge of the geochemical cycle of uranium and thorium in the earth's crust.

All major areas of relatively high-grade uranium deposits in the United States contain intrusive or extrusive igneous rocks of alkalic \* or calc-alkalic † affinity. The deposits are closely or distantly related to exposed or unexposed intrusives depending upon the available conduits for ore solutions. In impermeable igneous and metamorphic terranes where the porous structures are relatively short fractures, faults, and shear zones, the source rocks and the deposits show a close spatial relation. In terranes of permeable sedimentary rocks where single beds, or groups of interfingering beds, are continuous aquifers over large areas, the source rocks and uranium deposits may be either close together or many miles apart. Thorium, however, has a different field of chemical stability and consequently is deposited much more closely to its parent alkalic igneous rocks in associated carbonatites ‡ and veins; in fact, it occurs in the igneous rock itself and rarely is concentrated in porous sedimentary rock except as detrital grains.

Apparently the most favorable terranes for both metals in the United States are those containing small, near-surface intrusive and associated extrusive, alkalic igneous rocks that cut Mesozoic and Cenozoic terrestrial sedimentary rocks; less favorable are terranes containing deeply eroded granitic batholiths and their related pegmatites that cut Paleozoic and pre-Cambrian rocks. The absence of associated uraniferous pegmatites of similar age with most veins or bedded deposits of uranium indicates that deeper parts of igneous intrusives are less favorable loci for deposits than are the upper and peripheral parts of these masses. Marine sedimentary rocks rich in organic and phosphatic matter may be sources of low-grade syngenetic uranium deposits of large extent; they, like the impermeable terrestrial sediments, are hosts for high-grade epigenetic deposits only where adjacent to favorable structures that have been mineralized.

Broad geologic features commonly are delimited on maps at scales of 1:2,500,000 or larger in sufficient detail to focus attention on regions favorable for prospecting. Examples of favorable regions of igneous and terrestrial rocks of this order of magnitude include the Colorado Plateau and the pre-Cambrian, Paleozoic, and Triassic areas intruded by Triassic dikes and sills in the north-

\* In which the potassium- and sodium-rich varieties of the principal rock-forming minerals such as feldspar, pyroxene, and amphibole are predominant. [Ed.]

† In which the calcium-rich feldspars, pyroxenes, amphiboles, etc., are predominant. [Ed.]

‡ Metamorphic rocks rich in calcium or magnesium carbonates. [Ed.]



eastern United States. The Central Mineral Belt of Colorado and its possible extensions are an example of combined igneous and metamorphic terrane. By inspection of stratigraphic charts and logs, together with maps, it is possible to pick marine terranes favorable for syngenetic deposits such as the Northwest phosphate area of Idaho and Montana, the Florida phosphate area, and the Chattanooga shale area in Tennessee.

Because small-scale maps of major areas show only the larger intrusives exposed at the surface, the outer borders of favorable regions may be well beyond the limits of the igneous rocks mapped, perhaps by as much as several hundred miles, depending upon the presence or absence of permeable rocks and broad zones of deep-seated structures along which buried intrusives occur.

**Guides to new districts.** Within these broad regions the search for epigenetic deposits can be narrowed down to the smaller districts characterized by large faults, shear zones, folds, cryptovolcanic structures, diatremes,\* and buried or exposed intrusives. Structure contour maps of basement and other surfaces showing these important structures are most useful in conjunction with maps of structural features at the surface in delimiting the most likely locations of new districts. These favorable areas are in some places associated with abnormal though local increases in geothermal gradients as indicated by hot springs and high bottom-hole temperatures of deep wells. Such districts may be tens of square miles in extent, though their shape is commonly irregular, and within them the ore deposits are commonly localized in clusters.

The problem of finding new districts in permeable sedimentary terranes is one of finding large areas where physical traps favorable for the precipitation of uranium are numerous. Various guides have been successfully used in this phase of prospecting. These are the presence of favorable structures, host rocks, and chemical environment. Especially favorable are anticlinal or terrace structures—tectonic, erosional, or depositional in origin—or other structures that might cause the accumulation of gases or liquids such as  $\text{CO}_2$ ,  $\text{H}_2\text{S}$ , natural gas, and oil that could result in direct precipitation of uranium, or in precipitation of other solutes that in turn would reduce the solubility of uranium compounds. Some of these structures are places where fractures may allow the escape of dissolved gases and result in precipitation. Fault, shear, and fracture zones crossing sedimentary horizons at an angle to the direction of flow of solutions and primary sedimentary structures, such as channel, cross-bedding, and interfingering porous and less porous beds may change the velocity and pressure relationships and thereby result in precipitation.

Uranium and other metals also can be precipitated where the host rocks are not only structurally but chemically favorable; commonly both physical and chemical factors must be satisfied before an ore deposit can form. In meta-

\* Volcanic pipes and vents drilled through enclosing rocks by explosive forces. [Ed.]



morphic and igneous rocks porosity is usually low, except where influenced by tectonics; favorable chemical environments in these rocks are rare except in areas of marbles and high ferrous iron-rich rocks such as hornblende schist and gneiss. In the unmetamorphosed sedimentary rocks the porosity is greater and the ore is deposited as pore fillings. Coarse-grained sandstones with variable texture commonly make the best host for ore minerals; many uniformly sorted sands, though of high porosity and located in uraniferous terranes, are barren of ore. Below the zone of oxidation, wood and plant and other carbonaceous materials, carbonates, and clay minerals change the pH or otherwise cause reactions that result in precipitation; under oxidizing conditions iron and manganese oxides fix uranium readily.

**Guides to ore deposits.** Once a district has been found to contain abnormal concentrations of uranium, even though well below ore grade, various guides can be applied in the search for ore deposits. These can be grouped as structural, lithologic, mineralogic, and chemical; no single guide or group of guides is infallible.

Many methods have been used graphically to show these geologic guides. Structure contour and isopachous \* maps, on scales commensurate with the size of the feature being studied, have been used to good advantage to show the configuration and thickness of favorable formations, beds, lenses, and channel fills, as well as ore bodies, ore shoots, mineralized ground, and alteration zones. In the Black Hills of South Dakota and Wyoming, where uranium deposits appear most abundant on anticlinal and terrace structures, structure contours drawn on the top of the sandstone host rock have been used successfully in finding concealed deposits. Similar maps drawn on the base of the sandstone host on the Colorado Plateau have been used to delimit channels in which concealed deposits were found by drilling. Such maps used in conjunction with isopachous maps of the sandstone fill and of alteration zones in the underlying siltstones allow more accurate prediction of buried ore. Structure contour and isopachous maps also allow the location of zones of interfingering of sandstones and shales, favorable areas for deposits. Contour maps of facies changes and of the sandstone-shale ratio are also used; areas with a sandstone-shale ratio of 1:1 are very favorable for ore in some regions.

Maps showing the frequency of distribution of rock types, mineral types, grain size, and element or compound content of rocks, soils, plants, and waters are commonly used, together with other data, to outline areas for prospecting, and in some places, to direct exploration. Contour maps of the ground-water surface, together with maps of fluorine content in the water, have been used by D. M. Sheridan (personal communication) in the Red Desert area, Wyoming, as guides to the caliche-type schroëckingerite deposits. In North and South

\* Comprising lines drawn through points of equal thickness of a formation. [Ed.]



Carolina heavy mineral content obtained by panning gravels has been used to contour the favorability of broad areas as sources of monazite. These and many other techniques in common use by geologists have been adapted to the search for uranium and thorium with considerable success.

Epigenetic deposits of uranium in igneous and metamorphic terranes occur as fillings in fractures, faults, and shear zones; less commonly as replacements of limestone and other wall rocks. Veins containing Co, Ni, and Ag or Cu, Pb, Zn, and Ag minerals appear more favorable for pitchblende deposits than do other metal associations; Mo minerals commonly occur with brannerite, and Ti minerals with davidite. In the United States the epigenetic deposits are commonly clustered in areas close to post-Cretaceous igneous rocks and structures. Guides useful for finding ore in districts of this type are given below.

*Structural guides:* Explosion breccia and solution pipes, diatremes, or dikes; open or tensional parts of faults, fractures, and shear zones; contacts of dikes and sills; intersections of faults and fractures.

*Lithologic guides:* Dikes, sills, and small stocks of alkalie and fluorine-rich intrusives; carbonate, hornblende-biotite-, or garnet-rich wall rocks.

*Mineralogic guides:* Scattered yellow and green secondary stains and minerals on fractures or in altered wall rock; radioactive iron and manganese gossans; Co, Ni, and Ag minerals; Pb, Zn, Cu, Ag minerals; Mo minerals; Ti minerals; fluorescent silica druses\*; smoky quartz; dark purple to black fluorite; golden beryl; carbonate-feldspar gangue.

*Chemical guides:* More K than Ca and abnormal F in probable source rocks; more  $\text{Fe}^{++}$  than  $\text{Fe}^{+++}$  or high Ca in wall rocks; more  $\text{Fe}^{+++}$  than  $\text{Fe}^{++}$  in the veins; Bi, Co, Ni, Ag in vein material.

The guides to epigenetic deposits of thorium are similar to those for uranium except that ferrous iron in wall rocks does not appear to control deposition; secondary yellow stains are rare; abundant deep-red to purplish-red iron oxides are common; Nb, Ba, P and rare earths are abundant; carbonatite masses or veins are distinctive lithologic guides.

In the United States increasing numbers of uranium deposits are being found in deposition and structural basins filled with terrestrial sandstones, mudstones, and low-rank coal. Geochemical, botanical, and radiometric prospecting in such areas have been useful. Abnormal amounts of selenium, arsenic, iron, zinc, manganese, as well as uranium and vanadium in plants, soils, waters, and petroleum products aid in outlining areas favorable for the occurrence of uranium deposits. Many of these rocks are of Tertiary age and many contain or are associated with abundant volcanic debris, either as ash beds or as ash mixed with sand or mud. Considerable success in prospecting has been had by exam-

\* Crystalline cavity-lining incrustations. [Ed.]



ining areas of porous or carbonaceous beds beneath formations rich in volcanic debris on the assumption that uranium has been leached from this debris and concentrated in favorable beds in depth. These basins, however, are at altitudes of 3000 to 8000 feet and are areas of relatively recent crustal movement. They may have been much closer to sea level at the time of formation and later uplifted with concurrent mild flexing and faulting. Subsurface information in some places shows a general geographic correlation of "basement" highs—possible intrusives or deep-seated structures—and uranium districts; in other places buried faults appear important. The localization of individual deposits, however, appears to be more closely related to local favorable structure, host rocks, and chemical environment. Any of these factors may be the dominant control in any ore deposit, within a single area or in several areas. Guides that have been used to locate such deposits are summarized below:

*Structural guides:* Low anticlines, terraces, domes, or other structures showing abrupt changes in dip of permeable host rock below an impermeable cap rock; channels and swales \* cut in a relatively impermeable formation below the channel-filling sandstone host rocks; faults, fracture and shear zones, and breccia pipes; zones of sandstone interfingering with shales; thickened parts of lenses.

*Lithologic guides:* Cross-bedded, medium to coarse, variable textured sandstone; carbonaceous sandstones and shales; subbituminous coal and lignite, especially in contact with porous beds; pyroclastic-rich † beds overlying coal and sandstone; areas of abnormal quantities of iron and manganese oxides, carbonate, silica, or clay cements; clay pellet conglomerate and sandstone; carbonized wood; sandstone-shale ratio of about 1:1; abnormal colors in sandstone or shale, for example, white sandstone or mudstone grading into buff, yellow, red, brown, pink, or purple; colored sandstone altered irregularly white, gray, or green; red shale or siltstone altered to gray, green, or white below sandstone; abundant concretions of iron or manganese oxide, carbonate, silica; arkosic rocks.

*Mineralogic guides:* Yellow or green secondary incrustations or grains; jarosite ‡; iron-manganese carbonates; vanadium, silver, or copper minerals; carbon.

*Chemical guides:* Abnormal quantities of V, As, Se, Mo, Zn, Cu, Co, Ni, Mn, Fe, Ra, He in rocks, soils, natural gas, petroleum, asphaltic residues, surface and subsurface water; silicification of sandstone and shale enclosing carbonate-cemented sandstone; phosphate-rich sandstone.

\* Depressions. [Ed.]

† Volcanic ash, tuff, etc. [Ed.]

‡ Yellow to yellow-brown iron-potassium sulfate. [Ed.]



**Batholiths.** The batholithic areas of the United States have to date been relatively unproductive of uranium deposits. Few occurrences, other than in relatively small high-grade veins, have been found. The Boulder batholith in Montana has a few associated base metal-silver-uranium and chalcedony veins; the Sierra Nevada batholith contains only a few fissure-filling deposits; post-Devonian batholiths of the eastern United States contain pegmatites, but few veins; the Pikes Peak and associated batholiths of the Rocky Mountains contain some deposits, but these are much younger than the batholith. Thus it would appear that unless the batholith is cut by much younger rocks, such areas are not good prospecting ground for epigenetic deposits. Uraniferous pegmatites, however, are commonly associated with the pre-Cambrian, late Paleozoic, and in places Jurassic-Cretaceous batholiths. Thorium, in monazite, allanite, or thorite in igneous rocks, veins, and carbonatites is not uncommonly associated with the satellitic bodies of the batholiths.

In prospecting batholithic terranes particular attention should be given to (1) the smaller satellitic alkalic intrusives and associated carbonatites and veins as possible sources of thorium, (2) pegmatites, particularly those in country rocks of high metamorphic grade, and (3) veins that may be of younger age than the batholith.

**Continental shelf sediments.** Phosphorites and black shales are the only marine sediments that are known to contain abnormal amounts of syngenetic uranium. Prospecting for such low-grade deposits is a matter of analyzing radiometrically or chemically those shales and phosphorites found in field mapping or in petroleum prospecting. In the United States the gamma-ray logging records of oil and other deep wells in sedimentary terranes are a common starting point, although normally an evaluation of the area to be considered involves the delimiting of continental-shelf areas favorable for such sedimentation. The relative horizontal uniformity of composition of the shales and phosphorites over large areas necessitates prospecting for minor differences, but rarely is the order of magnitude of the grade changed.

**Placers in areas of granitic batholiths.** Monazite, zircon, and other minerals refractory to weathering that contain thorium and uranium are usually present in granitic batholiths in small amounts. Upon weathering of the batholiths these minerals commonly accumulate as placers, either as colluvial \* or alluvial material and as beach sands. Prospecting for such syngenetic deposits is based on (1) knowledge of the petrology and mineralogy of the igneous rocks of the area and (2) interpretation of recent or past drainage patterns and coastal history. Panning, rather than radiometric techniques, is the most useful method of prospecting alluvial placers, but air-borne surveying is most efficient for scouting present-day and fossil beach placers. Air-borne equipment also is most useful in delimiting source areas for placers.

\* Unsorted detrital material. [Ed.]



**Terrestrial and near-shore marine sediments.** Many near-shore marine sediments formed in deltaic, lagoonal deposits and other shore environments contain interlayered terrestrial phosphatic sands, carbonaceous debris, or coals that are capable of adsorbing uranium from sea water. Such rocks may then become low-grade syngenetic sources of uranium.

#### ROCK ALTERATION CRITERIA \*

Alteration criteria associated with uranium mineralization have received less attention than the phenomena merit because (1) radioactivity counters and scintillation devices often furnish a direct indication of ore bodies, (2) alteration criteria often are not recognized in thick sedimentary sections, (3) many effects, such as the red stain which accompanies some pitchblende veins, are very localized.

Alteration effects associated with uranium mineralization in igneous or metamorphic rocks appear to be more readily detected than those in sediments. The argillic † halos which accompany the veins at Marysvale, Utah, in quartz monzonite, are easily recognized features. On the other hand, alteration effects in Colorado Plateau sediments are sometimes more subtle.

Few if any of the alteration criteria associated with uranium deposits differ appreciably from those of copper, zinc, tungsten, and other metals. However, their applicability to uranium is selective. The term alteration is applied here to the development of clay mineral halos, chloritization, alunization, fluoritization, carbonatization, silicification, and ferrugination. It is perhaps noteworthy that the criteria of contact metamorphism in general have not been applicable to the United States uranium deposits.

**Alteration types.** The significant alteration effects in certain uranium and metal deposits are believed to be indicative of hydrothermal activity.

Hydrothermal solutions traversing faults, fractures, or shear zones generally react with the wall rock so that a sequence of alteration develops. Although the sequence may vary with the character of the rock, chlorite and montmorillonite are two of the earliest minerals to form at the expense of the wall rock; they tend to be prevalent around the margins of altered areas. Somewhat later, and in a more centralized position, kaolinite, some montmorillonite, and often illite (hydrous mica) occur. At the core of the altered area dickite ‡ may be associated with kaolinite, or kaolinite with illite. Often sericite and silicification are found at the center. Although no two districts in which alteration of this type has been described are identical, most exhibit a progressive

\* From Geneva Conference Paper 502, "Rock Alteration Criteria in the Search for Uranium" by Paul F. Kerr, Columbia University.

† Clay mineral. [Ed.]

‡ One of the kaolin minerals. [Ed.]



sequence of various degrees of wall-rock replacement. Maps of these altered areas frequently reveal important trends in metallic mineralization which may favor certain of the alteration stages.

The types of hydrothermal alteration, believed to be related to the general process of uranium emplacement, particularly in the western United States, include: ferrugination, fluoritization, chloritization and argillization, alunitization, and dolomitization.

**Ferrugination.** Iron is one of the most common elements associated with uranium. In fact, the identification of pitchblende may be hindered by the intimate mixture of fine-grained pyrite. In the replacement of wood in logs and other plant remains of the Shinarump conglomerate at White Canyon, Utah, cells of wood may be filled either with pyrite, chalcopyrite, or bornite, and cell walls may be replaced by pitchblende.  $H_2S$  derived from decayed vegetation is thought to have fixed the iron in the sulfide form.

Hematitic alteration produces various shades of red which are found with certain veins in the Canadian Shield and in the Sunshine mine, Idaho, where color intensity varies directly with the amount of pitchblende. It is thought that during hypogene vein formation, given sufficient temperature, the ferrous ion may change the uranyl ion to the uranous ion and thus cause the precipitation of pitchblende. At the same time the resultant ferric iron forms hematite, which is essentially colloidal and acts as a pigment for the accompanying colloidal silica. Dawson has called attention to the hematitic alteration of wall rock with pitchblende-bearing veins in the Goldfields region, Saskatchewan, Canada. A somewhat similar coloration is found at depth in some of the Marysvale veins.

Masses of siderite are found near the uranium ores of Temple Mountain, Utah. Field and analytical data seem to indicate that the upward-moving thermal solutions removed iron from the underlying ferruginous sediments and redeposited it as siderite in veins and replacement masses at a higher level. Although the uranium occurs in asphaltite, it may be closely associated with pyrite. A nodule of this material is illustrated in Figure 7.1.

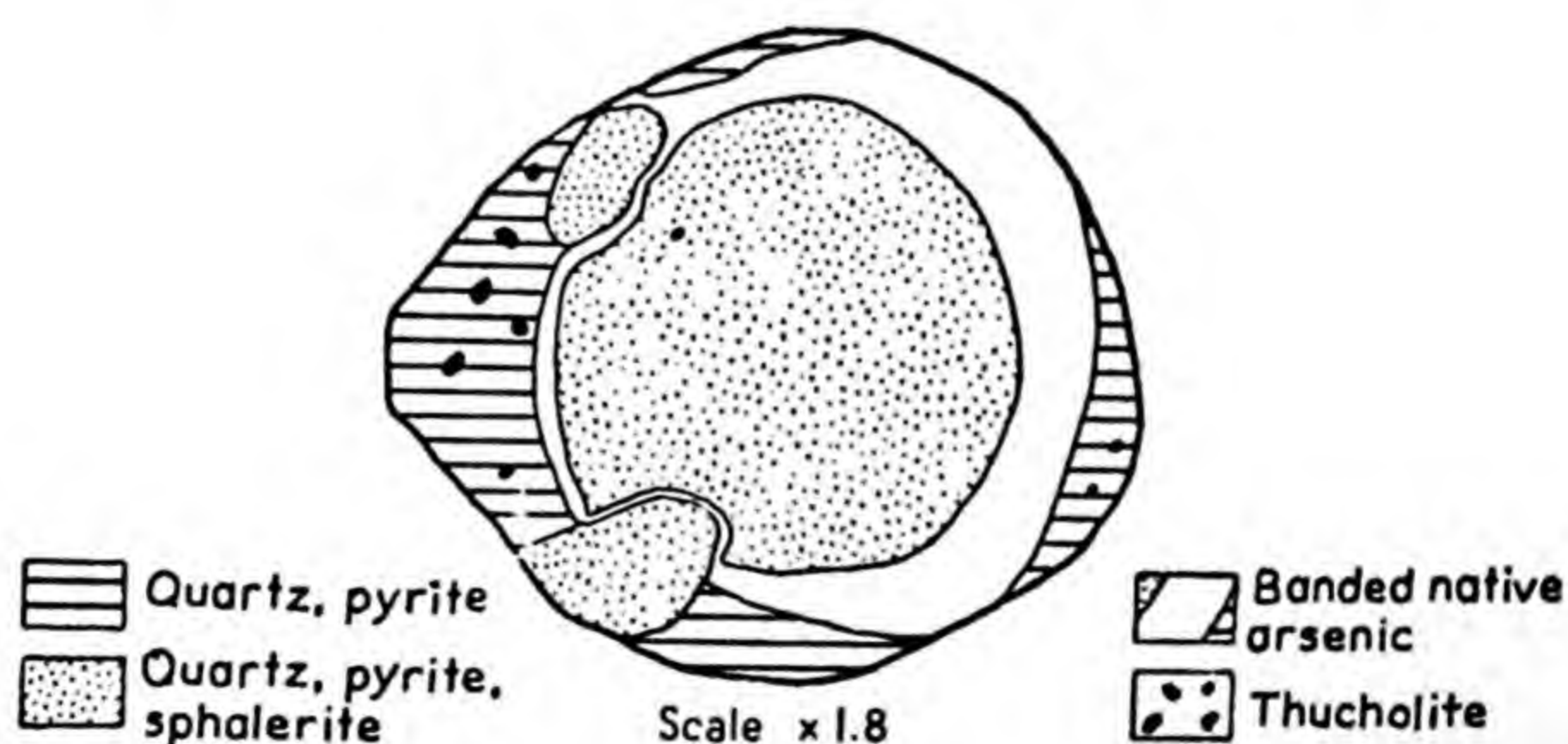


FIG. 7.1. Cross section of pyrite-native arsenic nodule, Temple Mountain, Utah.



**Fluoritization.** Since the oxides  $\text{UO}_2$ ,  $\text{ThO}_2$ ,  $\text{CeO}_2$ , and  $\text{CaF}_2$  all have a face-centered cubic "fluorite" lattice with a unit cell close to  $5.50\text{\AA}$ , it is not surprising that they prefer the same geochemical environment. According to Phair and Shimamoto, who describe euhedral uranothorite inclusions in fluorite, it seems probable that the association of uranium, thorium, and rare earth minerals may prove extensive in fluorite-rich hydrothermal deposits. Kerr and Dahl note microscopic particles, presumably pitchblende, in highly radioactive fluorite at Grants, New Mexico. Brown and others note an interesting radioactive anomaly which is associated with fluorite at Hicks' Dome, Illinois. Bray reports pitchblende in fluorite which is associated with pyrite, galena, and sphalerite at Jamestown, Colorado; and Lovering describes radioactive fluorite in veins and pipelike bodies east of Beatty, Nevada. Often, black or extremely dark purple fluorite is associated with radioactivity at Marysvale. In fact, the prevalence of this material in a western area is frequently considered significant in the search for uranium.

**Chloritization and argillization.** Argillic alteration associated with uranium mineralization is illustrated at Marysvale, Utah, where an air-borne radiometric survey of the mining area shows anomalies which correspond to areas of alteration. The area in which the effects are most noticeable is about seven miles square, and it is clearly outlined by white or iron-stained clay. The clay-filled channels which constitute the veins at Marysvale vary widely in their clay and uranium content. However, they provided the conduits along which uranium-bearing solutions migrated upward, as shown by a radiometric comparison of the wall rock and vein. The principal uranium mineral of the veins is pitchblende (Fig. 7.2), although secondary uranium minerals are found

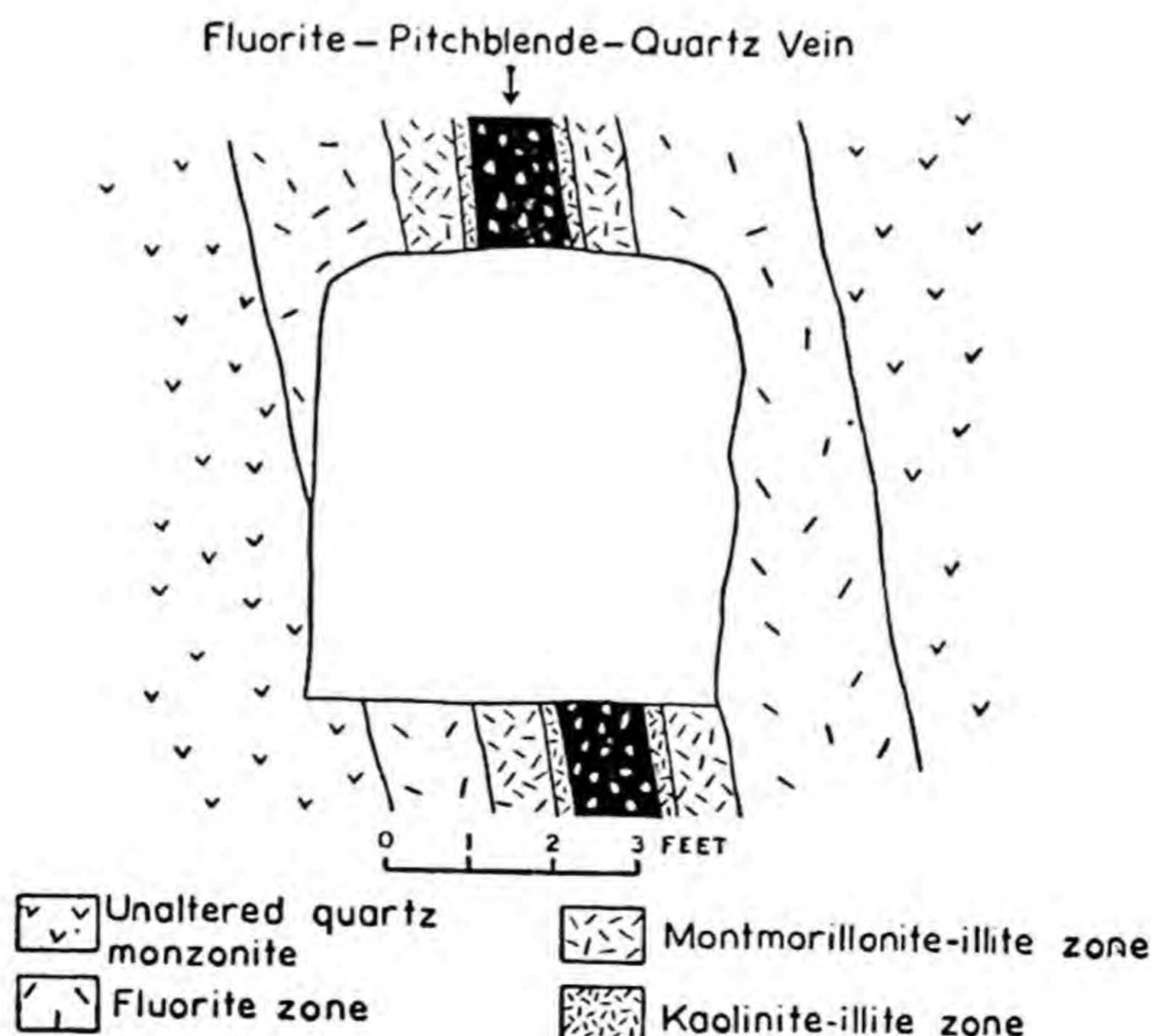


FIG. 7.2. Pitchblende vein, Marysvale, Utah.



near the surface, and the rare uranium molybdenum mineral, umohoite, occurs in one of the mines.

The association of argillic alteration and pitchblende is most frequent at Marysvale in the quartz monzonite. Preceding alteration, the feldspars are lustrous and the ferromagnesian minerals, if present, are usually unchloritized. As alteration is initiated, a chloritic zone develops in which plagioclase tends to become dull and biotite chloritized. This occurs not only at Marysvale but also at places in the Boulder batholith in Montana, in southwestern New Mexico near Silver City, and along the Colorado Front Range. Rocks in which ferromagnesian minerals are scarce may yield a montmorillonite rather than a chloritic zone.

The two most prominent clay minerals of the dominantly argillic stage at Marysvale are montmorillonite and kaolinite. As alteration becomes more intense, rock texture is destroyed and illite develops. In places this stage is accompanied by the introduction of fluorite. The main precipitation of pitchblende and pyrite is believed to occur toward the close of the argillic stage or perhaps later.

Patches of alteration which are similar to those at Marysvale are found within a radius of twenty miles. It would appear, therefore, that the alteration is widespread, and comparatively recent, since determinations of the Marysvale pitchblende by Dr. J. L. Kulp indicate an age of about ten million years. It is of interest to note that patches of alteration, perhaps an extension of the Marysvale pattern, have been observed in volcanic rocks near the margin of the Colorado Plateau. A center of hydrothermal activity, if concealed beneath the sediments of the Plateau, could have provided a source for the accumulation of uranium in sediments.

Recent studies along the San Rafael Swell, Utah, and elsewhere contribute criteria which may provide an approach to the problem of alteration and uranium in sediments. Weeks reports gray shale at the Scenic No. 4 claim in the White Canyon area, Utah, which is completely kaolinized. Green clay zones, although widely distributed in the Mossback conglomerate of the San Rafael Swell, have not as yet been found to be related to ore deposition. However around the inward facing escarpment, faults accompanied by bleaching and sometimes uranium mineralization cut the Mossback conglomerate and related members of the Chinle formation. These bleached areas are yellowish brown, in contrast to the adjoining red or dark-brown strata, and appear to extend up along fault lines with an appearance of enlargement in the Chinle siltstone above the Shinarump.

Laboratory study of this bleached material indicates the presence of kaolinite and illite. Although further investigation is necessary, it would appear that the form and mineralization of the bleached zones suggests upward-migrating



solutions. Since significant uranium mineralization occurs in connection with one such zone at Temple Mountain, this criterion seems worthy of consideration.

**Alunitization.** The presence of alunite in the vicinity of uranium deposits is frequent, although the relationship and significance remain largely undetermined. At Marysvale, extensive areas of alunite have formed by hydrothermal alteration of tuffs and pyroxene andesites. The major hydrothermal alunitization seems to precede uranium mineralization, but there is some alunite which is an end-stage effect.

Alunite and kaolinite have been found in veinlets in the Mossback conglomerate at Temple Mountain where they occur around the margin of the ore-bearing area, and seem to resemble caliche in outcrop. Alunite is reported in several of the other Plateau uranium deposits. Gruner and Gardiner report it in the Moenkopi of the Capitol Reef area, Utah; at Deer Flats north of White Canyon; and southeast of Fruita, Utah. Weeks finds alunite at the Skyline claim, Monument Valley, Arizona, where it fills joint cracks in altered arkosic sandstone.

**Dolomitization.** Dolomitization of the Wingate sandstone (Fig. 7.3) occurs at several places on Temple Mountain where it forms distinctive brown patches.

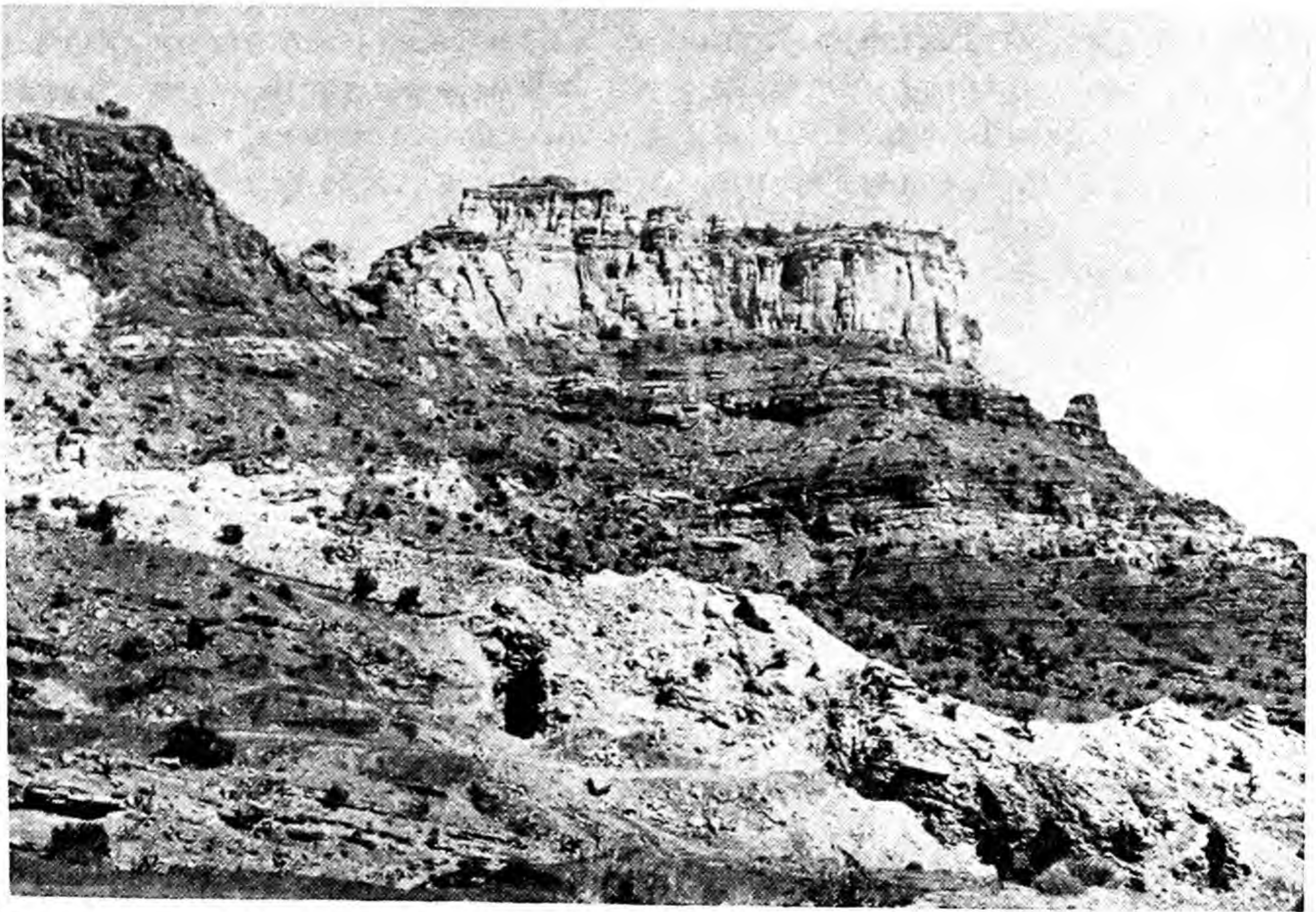


FIG. 7.3. Alteration and collapse features at Temple Mountain, Utah. Dark dolomitic area (crest of hill left) with normal Wingate strata on right. The bleached area in the foreground is a collapse feature. The cut in foreground produced uraniferous asphaltite.



This remarkable change from a rather pure eolian sandstone to a massive dolomite is gradual, but it occurs in three stages.

The first stage of dolomitization is "nodular impregnation" in which nodular dolomite surrounds suspended unaltered sand. These forms have an average diameter of about one half inch, and occur in areas which vary from a few to hundreds of feet. They tend to follow the Wingate sandstone, but may extend across the beds or occur in irregular masses which penetrate the underlying Chinle sandstone. The second stage is "interstitial impregnation." Here, replacement by dolomite of the quartz grains within the nodules occurs, as well as in the areas between the nodules. In thin section a radial strain which is relict of the nodular form may be present. The third stage is "massive replacement" in which the nodular development is completely obliterated and the Wingate sand grains are completely replaced.

The relation between dolomitization and uranium deposition is indirect. The dolomite at Temple Mountain occurs near areas of solution stoping which are referred to as "collapse features." These have been interpreted as breccia pipes, but it seems likely that they result rather from solution and collapse. Thermal solutions which penetrated carbonate and arenaceous sediments have produced cavities into which great blocks of overlying strata have fallen. The collapses seem to be funnel shaped in cross section and to originate along faults. Their surface exposure is circular or elliptical with a maximum diameter of 1000 feet. Although uranium is sparse in these areas, it occurs nearby in larger amounts. The uranium-bearing asphaltite is found in veinlike masses which cut the dolomite. The emplacement of uranium therefore seems to be later than dolomitization.

It seems reasonable to postulate that the same sequence of solutions which removed calcium and magnesium from the underlying strata and deposited them in the Wingate sandstone as dolomite also could have introduced the uranium. Scattered uranium occurrences throughout a vertical length of 1500 feet of exploratory drilling seem to support this theory. It is likely, therefore, that the dolomitic areas at Temple Mountain are indicative of solution action on sediments. This, in turn, may indicate that on the San Rafael Swell at least, dolomitization may suggest nearby uranium emplacement.

**Silicification.** The relation of silicification to uranium mineralization is worthy of consideration. Often there is no immediate application to uranium discovery, as illustrated by the silicified logs in the uranium deposits of the San Rafael Swell. Large masses of Mossback conglomerate are silicified, although as yet they have failed to yield uranium. Nevertheless, areas of silicification in the vicinity of uranium deposits merit investigation. One surface mass of silicification at Marysvale overlies an extension of the Bullion Monarch vein system, a system which has been highly productive of uranium. In this area, cherty quartz stringers are associated with high-grade pitchblende ore, and the



fluorescence of chalcedonic nodules may be due to contamination with uranium. The role of silicification probably varies with the type of deposit, the generations of mineralization, and the associated rock types.

**Conclusion.** The criteria of rock alteration which are useful in the search for uranium bear a striking resemblance to those for other metals. However, conditions may vary with the locality, and render recognition much more difficult. This is true of the Colorado Plateau sediments when compared with igneous or metamorphic areas. Argillic alteration and dolomitization are believed to represent earlier stages in the ore-forming process in the sediments at Temple Mountain. Significant alteration features in hydrothermal uranium deposits appear to include: ferrugination, as shown by widely distributed pyrite and hematitic coloration; fluoritization, as shown by the association of fluorite and pitchblende; chloritization and argillization as shown by wall-rock alteration which follows or accompanies uranium emplacement; alunitization, depending upon depositional environment; and dolomitization, as shown by its proximity to uranium deposition.

### HEAVY MINERALS

\* The search for uranium ore bodies by panning or loaming of alluvial concentrates is seldom undertaken, for uraninite (pitchblende) and its secondary alteration products are virtually unknown in modern sediments because of the ease with which they are pulverized and dissolved during transportation. Complex uranium minerals such as euxenite, betafite, brannerite, and samarskite readily survive in placers, as do also monazite, thorite, and thorianite; and although in almost every case these minerals derive from pegmatites and granites too low in grade to be payable, instances have been known where pebbles of monazite and grains of thorianite have been traced back to workable deposits. The study of the derivation of radioactive placer minerals should therefore not be neglected by the prospector.

† A method of geologic prospecting has been developed for use in areas underlain by crystalline rocks whereby the relative abundance and distribution of detrital heavy minerals are compared to show regional relations among the rocks and minerals. It is based on the assumption that differences among the suites of detrital minerals from streams with small drainage basins reflect variations in the composition of bedrock if other factors, such as hydraulic influence, are similar. As originally developed, the method was used to study the occurrence of monazite in igneous and metamorphic rocks, but the system is adaptable

\* From Geneva Conference Paper 764, "Methods of Prospecting for Uranium and Thorium" by C. F. Davidson and S. H. U. Bowie, Geological Survey of Great Britain.

† From Geneva Conference Paper 505, "Heavy Mineral Prospecting" by W. C. Overstreet, P. K. Theobald, Jr., J. W. Whitlow, and J. Stone, U.S. Geological Survey.



to rapid reconnaissance studies of the distribution of other economic minerals.

The method is well suited to intensely weathered regions with deep residual soil where heavy minerals recovered from the headwaters of small streams have been derived from underlying or adjacent rocks. Similar methods can be used for geologic prospecting wherever the stream density is adequate and there is no interference from glacial deposits.

**Field work.** Field work consists of taking heavy-mineral concentrates and making normal reconnaissance geologic studies. Collecting concentrates is done first because it is merely manual labor, progresses rapidly, and allows the geologist to become acquainted with the terrain. It is followed by geologic studies at a reconnaissance scale suited to the over-all needs of the problem. No innovations have been introduced into the reconnaissance; it involves familiar geologic procedures planned to give the desired knowledge of types, trends, and distribution of the rocks.

Heavy-mineral concentrates are collected from equal-sized samples of gravel taken from riffles in the channels of small streams. Areas of the distributive provinces of the streams above the sites sampled should not exceed two square miles. Uniformity in the position in the stream channel and grain-size distribution of the samples is desirable to reduce the effect of variable hydraulic influences upon the heavy-mineral suite. If external influences are similar, then changes in the mineralogy of the concentrates will reflect variations in the aggregate composition of the rocks underlying the distributive provinces of the streams.

Similarity in position of the alluvial samples can be assured by adequate planning before entering the field. The most desirable localities, as regards size of distributive province, length and gradient of stream above locality sampled, and proximity to adjoining samples, are plotted on suitable maps. Once field work is begun, the net of proposed localities is modified to fit actual conditions and to increase uniformity among the samples.

Uniformity in grain-size distribution is maintained by visual inspection and selection of samples that contain gravel having the same maximum intermediate dimension. Equal-sized samples of alluvium are measured volumetrically, since no system of dry weighing is adapted to rapid reconnaissance and the wet weights of the samples are too variable to be meaningful. Enough gravel is taken from the stream (generally 0.3 cubic foot) to provide a volume, after screening to minus  $\frac{1}{8}$  inch, of a clay- and silt-free product, adequate to make one charge for a standard 16-inch gold pan.

The screened product is panned to produce a concentrate that contains from 5% to 20% quartz and other minerals of low specific gravity. Panning, which takes about twenty minutes per sample, is carefully done and is the only form of concentration used either in the field or laboratory. No further cleaning is required.



The gold pan is not used as a quantitative tool; mineral distribution is interpreted on a comparative basis; hence, total recovery of the heavy minerals is not required. All that is needed is consistent panning of each sample from one sample to another to insure similar effective concentrations.

Heavy-mineral concentrates are also prepared from bulk samples of bedrock or residual soil so that relations can be determined between the suites of detrital minerals and rocks in the area. There is some danger that this might become a study in itself and impede heavy-mineral prospecting. To forestall such a shift in emphasis during reconnaissance, not more than 5% of the total number of samples should be taken from bedrock.

No improvement in geologic resolution is gained by doubling the number of samples taken in a given area. Significantly greater resolution can be attained if the number of samples is increased to scores per square mile, but the method can then no longer be regarded as reconnaissance.

**Laboratory work.** Periodically the samples are shipped to a central laboratory for examination. Mineralogic identification, grain counts, and computations are done in the laboratory by a staff who are acquainted with the field problem. Since the usual study involves several thousand samples per year, mineralogic work must be reduced to a routine consonant with the time available and the accuracy required. Mineralogic analyses of the concentrates are done most efficiently along "assembly line" plans with the operation divided into (1) removal of magnetite from the concentrate and weighing, (2) sieving the magnetite-free concentrate and weighing the fractions, (3) splitting, (4) counting, and (5) calculating. The first three operations are done by an aid, the fourth is done by the mineralogist, and both participate in the calculations.

Magnetite is removed from the concentrate with a hand magnet and weighed. The magnetite-free concentrate is separated into three to five sieve fractions, depending upon the range in size of grains in the concentrate, and the weights of the fractions are recorded. A split of 100–200 grains from each fraction is poured into a narrow groove milled in a plastic slide designed for use with a binocular microscope. The slide is placed on the stage of the microscope and passed along as the split is examined. All the grains of one mineral are counted in one traverse; all the grains of a second mineral are counted in the second traverse, and so on until all mineral species in that sieve fraction of the concentrate are counted. Two concentrates can be counted per hour. Use of the binocular microscope decreases the time consumed in preparing slides for counting, reduces fatigue, and permits other analyses to be made on any grain.

Large splits are counted periodically to check representation of the smaller cuts, and the spot identifications of minerals are supplemented as required by oil immersion, spectrographic, and X-ray techniques.

Computations performed in the laboratory are those needed to convert grain counts to weight per cents of the concentrate. Conversions relate specific grav-



ity, size, and frequency distribution to weight per cent through assumptions that specific gravity is constant in a given species and that all species in a given sieve fraction have the same volume. Obviously, the specific gravity of a given species and the volume of grains in a given sieve fraction vary, but as long as all grain counts are recalculated in the same fashion, the relative differences among the concentrates are preserved.

The calculations can be performed in about five minutes and consist of the following:

1. Weight per cents of the magnetite and the sieve fractions are calculated directly from their weights and that of the concentrate.
2. The grain counts of each mineral are converted by specific gravity factors into units equivalent to the number of similar-sized grains of quartz needed to equal the weight of the heavy mineral.
3. The units in each sieve fraction are totaled.
4. The weight per cent of a sieve fraction is divided by the total number of units in the fraction, and the quotient is multiplied by the number of units of each mineral in the fraction to give weight per cent of that mineral in that fraction.
5. The last three operations are repeated for each sieve fraction.
6. The sum of the weight per cents of a given mineral in all the sieve fractions equals the weight per cent of that mineral in the concentrate.

Mineralogic analyses of the alluvial concentrates are compiled on maps showing sample numbers and localities. Separate maps are used for each mineral. The compositions of concentrates obtained from bedrock or residual soil are not shown on maps used for alluvial concentrates.

The weight per cent of a mineral is plotted at each locality where it is 1% or more of the quartz-free concentrate. Recalculation of the mineralogic analyses reported from the laboratory to a quartz-free basis is readily done by means of a nomogram. Recalculation is most conveniently accomplished at the time the minerals are plotted on maps, because the geologist may wish to exclude several other minerals, such as feldspar, biotite, and hematite, from the recalculated concentrate.

The abundance of each mineral, expressed as weight per cent of the quartz-free concentrate, is contoured at suitable intervals on a transparent overlay, which protects the base map from the corrections incident to contouring. Final copy is prepared from the overlay and is reduced photographically to a scale appropriate to the area and the density of sampling. A compilation scale of 1 inch = 2 miles and a final scale of 1 inch = 4 miles was satisfactory for an area of 4000 square miles where 2500 samples were taken.

Contours are drawn at intervals suited to the range in weight per cents spanned by the different heavy minerals. Supplementary contours at partial



intervals are an excellent means of showing detail in critical ranges of weight per cent. Table 7.1 shows contour intervals that were used satisfactorily in the 4000 square mile area mentioned above.

TABLE 7.1

Mineral	Initial Contour (weight per cent)	Contour Intervals (weight per cent)	Maximum Contour (weight per cent)
Ilmenite . . . . .	10	10	90
Magnetite . . . . .	1	10 <sup>a</sup>	90
Rutile . . . . .	1	5	20
Garnet . . . . .	1	10 <sup>b</sup>	70
Zircon . . . . .	1	10 <sup>c</sup>	50
Monazite . . . . .	1	10 <sup>a</sup>	80
Xenotime . . . . .	1	10 <sup>a</sup>	20
Tourmaline . . . . .	1	5	30
Spinel . . . . .	1	1	6
Sphene . . . . .	1	1	3
Staurolite . . . . .	1	5	90
Kyanite . . . . .	1	5	25
Sillimanite . . . . .	1	5	35
Epidote . . . . .	1	5	80
Hornblende . . . . .	1	5	50

<sup>a</sup> Included a supplementary contour at 5%.

<sup>b</sup> Included supplementary contours at 5% and 15%.

<sup>c</sup> Included supplementary contours at 2% and 5%.

The mineralogic analyses of concentrates from bedrock and residual soil are plotted at the same scale, and data from the reconnaissance geologic studies are similarly compiled to assist interpretation of observations.

**Interpretation.** The heavy-mineral contours are interpreted to guide selection of areas where further geologic studies would have the greatest probability of revealing ore deposits.

The sources of most of the detrital minerals are shown by the heavy minerals concentrated from bedrock or residual soil. Thus the general pattern made by the mineralogic contours can be related to changes in proportions of the different major rocks in the area examined, and the pattern of the contours will conform to the regional trends discovered in reconnaissance.

Antipathetic zones of metamorphic minerals reflect different grades of regional metamorphism and differences in the composition of the bedrock. The first



appearance of detrital chloritoid, staurolite, kyanite, garnet, and sillimanite is as precise a guide to the position of an isograd as is location by petrographic study.

The general concordance or discordance of granitic rocks is shown by the conformity of contours for zircon and monazite to the contours of metamorphic minerals; an angular difference between the contours shows the trend of discordant plutons.\* Typical contact metamorphic minerals appear peripheral to the bodies that produced them.

Local mineralogic "highs," where one or more minerals abruptly rise in abundance over their average distribution, reflect changes in the gross composition of the bedrock. Such "highs," where resistant ore minerals or resistant heavy minerals associated with soluble ore are concentrated, become the loci for normal geologic study.

#### EXPLORATION OF SHINARUMP CHANNELS, COLORADO PLATEAU †

Paleostream channels filled with Upper Triassic Shinarump clastics, which in many places on the Colorado Plateau contain uranium ore bodies, may be traced by drilling based on information derived from contour maps of the lower contact of the Shinarump. Such maps, if corrected for the effects of dip, are reasonable approximations of the pre-Shinarump erosion surface. The presence of ore in channel fills may be indicated by various empirical criteria. In White Canyon 22 channels, 6 containing ore, and in Monument Valley 14 channels, 7 containing ore, were located by recognition of certain geologic criteria and traced by drilling guided by information interpreted from paleotopographic maps.

**Geology of paleostream channels.** Monument Valley is at the southern end of the Monument uplift, the north end of which is near the junction of the Green and Colorado Rivers; White Canyon is on the west flank of the same anticlinal structure; Circle Cliffs, another area where Shinarump channel ore deposits are frequent, is a northwest-trending uplift in Utah. Folding of these structures postdates the paleostream channels. The influence of structure on primary uranium mineralization and its subsequent redistribution is not clear.

Shinarump clastics normally lie on Moenkopi (Triassic) redbeds, but where these have been removed by ancient stream erosion, the clastics rest on Permian rocks. After deposition of Moenkopi redbeds, ancient streams removed portions or all of that formation and left channels of varying sizes cut into the erosion surface. The intervening areas were eroded to gently ir-

\* Intrusive bodies; in this case, granites. [Ed.]

† From Geneva Conference Paper 517, "Techniques and Guides for Exploration of Shinarump Channels on the Colorado Plateau" by H. B. Wood and W. D. Grundy, U.S. Atomic Energy Commission.



regular surfaces of low relief. A period of deposition of the Shinarump followed, filling the old stream channels with clay, silt, sand, and gravel and covering much of the erosion surface (Fig. 7.4). Some paleotopographic highs remained free of Shinarump deposits and at various places the overlying Chinle formation into which the Shinarump grades laterally and vertically rests directly on the Moenkopi.

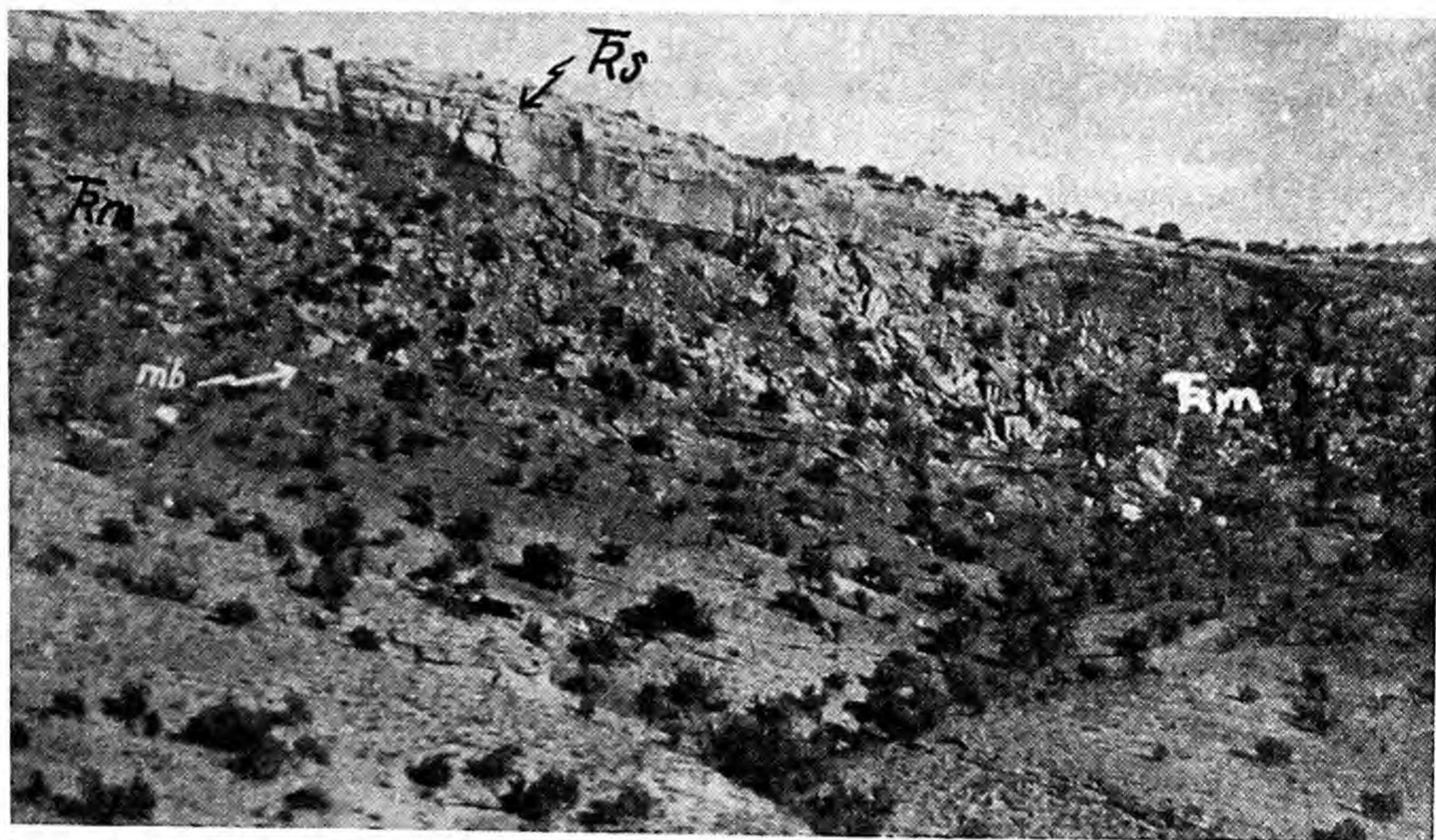


FIG. 7.4. Aerial view of a Shinarump channel, Colt Mesa, Circle Cliffs, Garfield County, Utah. Trs = channel, mb = marker bed, in Moenkopi formation (Trm).

Paleostream channels may vary in length, width, depth, cross-sectional profile, and trend within the same region. They may be subparallel or convergent; some meander, bifurcate, and rejoin; some may die out against paleotopographic highs. A few channels may be traced for miles; others only a few thousand feet.

Most channels in Circle Cliffs and Monument Valley are from 300 to 3000 feet wide and 30 to 275 feet deep. Scour depths along the axis of a channel vary as much as 60 feet, a circumstance similar to that in the channel of the modern Platte River in Nebraska. Channels in White Canyon are from 75 to 300 feet wide and 10 to 50 feet deep, and depths of scouring along the axis of the same channel vary as much as 40 feet.

Many paleostream channels are easily recognized at their outcrops by truncation of underlying Moenkopi beds and by thickening of Shinarump sandstones. Others, such as the broad basin at the Happy Jack mine in White Canyon, are difficult to recognize at the outcrop, but are clearly indicated by paleotopographic maps developed from drilling.



The sediments filling paleostream channels are a heterogeneous mixture of cross-stratified sandstones with lenses of mudstone and conglomerate. In general, the coarser clastics of sandstone and conglomerate are most abundant in the lower portions of a channel, but sandstone is dominant throughout the channel fill. Carbonaceous material, silicified wood, and asphaltic material are generally present in minor quantities, although locally they may be more concentrated. The asphaltic material may extend downward into the underlying Moenkopi.

**Uranium ore in channels.** The largest ore bodies in Monument Valley and in White Canyon are measured in hundreds of thousands of tons, and in Circle Cliffs, in thousands of tons. All ore bodies in these regions are roughly tabular, generally parallel to stratification and to the channel trend.

Most ore bodies are in the coarser clastics near the base of a channel, and mineralization may extend across the contact into the underlying formation. In Circle Cliffs about 80% of the production has come from the Moenkopi formation underlying channel flanks. At Monument No. 2 mine in Monument Valley the upper six feet of the De Chelly sandstone member of the Permian Cutler formation, underlying the Shinarump channel, contains ore. In this exceptionally large deposit, most ore is near the channel base, but some occurs in the uppermost part of the channel fill as high grade lenses extending in from the flanks. At White Canyon and in Monument Valley, most ore is in sandstone filling the deeper scours within channels; a lesser quantity occurs along channel flanks.

**Geologic controls and guides.** Controls are those geologic conditions which influenced the movement of uranium-bearing solutions and the precipitation of uranium minerals. Guides are those mineralogic features which are repeatedly associated with uranium deposits. The order of importance of recognized controls and guides varies from region to region, and none are positive indicators. However, the probability of encountering ore at any one locality increases with the number of indicators found.

1. A paleostream channel filled with Shinarump clastics is an important control of mineralizing solutions.
2. Within channels, irregular depths and trends appear favorable for mineralization. Deeper scours which form closed basins are most favorable.
3. An abundance of carbonaceous and asphaltic material in the lower portion of a channel is a common associate of uranium ore. In many localities, carbonaceous material is impregnated or replaced by uranium minerals. However, many uranium ore bodies are locally devoid of carbonized plant debris.
4. A poorly sorted, porous, arkosic, argillaceous sandstone or conglomerate containing moderate amounts of interstitial clay, claystone seams, and clay



pellets, associated with carbonaceous material, is lithologically favorable for deposition of ore. The content of argillaceous material in the lower part of a channel fill, however, should be about 25% of the total to be favorable.

5. A thin zone of bleached Moenkopi immediately beneath the Shinarump is almost universal. However, a thickening and intensification of the bleaching occurs beneath many uraniferous channels.
6. Copper sulfides, sulfates, and carbonates; iron sulfides, sulfates, and hydrous oxides; and cobalt arsenate, sulfate, and carbonate are conspicuous associates of many uranium deposits; hence their presence on an outcrop of channel sand is a suggestion that ore may be nearby.
7. In regions of non-vanadiferous uranium deposits, channels extending beneath thick, relatively impervious cover, or below a water table, offer more favorable ground for exploration than channels under thin pervious cover which have been exposed to oxidation and leaching by ground water. The White Canyon and Circle Cliffs non-vanadiferous uranium ores of pitchblende associated with base metal sulfides commonly form soluble uranyl sulfates when oxidized. The larger White Canyon deposits have been protected from oxidizing ground waters by thick, impervious cover, whereas in Circle Cliffs nearly all deposits underlie pervious sandstone benches and have been oxidized and leached. The uranium-vanadium ores of Monument Valley form relatively insoluble uranyl vanadates when oxidized, so the thickness or permeability of the cover is less important.

**Mapping techniques for reconstruction of paleotopography.** Because all uranium ore bodies in the regions under discussion are in Shinarump channels, prospecting has been confined to a search for paleostream channels using the criteria listed above. Where such a channel or a suggestion of a channel is found, the base of the Shinarump and at least three points on some marker bed below it are mapped with a plane table and alidade. Elevations on a marker bed are used for the determination of local dip and strike. Elevations of the base of the Shinarump must be corrected for the effects of regional dip in order to show the paleotopography by contours. In areas over which there is no appreciable change in regional strike, the dip correction is straightforward. Where both strike and dip vary across an area, another procedure may be applied. This method requires numerous exposures of marker bed around the area. The base of the Shinarump is mapped, as well as a marker bed below the Shinarump. A structure contour map of the marker horizon is next prepared. Allowing the highest structure contour to serve as a hinge (the line of no correction), to each surveyed elevation point on the base of the Shinarump is added that figure (dip correction) which is the



difference between the elevation of the hinge and that of the structural contour on the marker bed immediately below that point on the Shinarump. Then by using the dip-corrected elevations of plane-table points on the base of the Shinarump, the Shinarump paleotopography may be reconstructed by contouring. The trend of the trough or low indicated by the contours is projected from the rim outcrop and the validity of the projection is tested by drilling.

#### SELECTED REFERENCES FOR CHAPTER 7

- Brophy, G. P., and P. F. Kerr, 1953: *Hydrous Uranium Molybdate in Marysvale Ore*. U.S. Atomic Energy Commission RME-3046.
- Dawson, K. R., 1951: *A Petrographic Description of the Wall Rocks and Alteration Products Associated with Pitchblende-bearing Veins in the Goldfields Region, Saskatchewan*. Dept. of Mines and Technical Survey, Geological Survey of Canada, Paper 51-24.
- Everhart, D. L., and R. J. Wright, 1953: The geologic characters of typical pitchblende veins. *Econ. Geol.* 48:77-96.
- Kerr, P. F., and H. Dahl, 1953: *Uranium-fluorite Association in the Todilto Limestone, Grants, New Mexico*. U.S. Atomic Energy Commission RME-3051.
- Kerr, P. F., and D. M. Laphan, 1954: Report on a nodule from Temple Mountain. *Annual Report*, U.S. Atomic Energy Commission RME-3096:7-15.
- Kerr, P. F., and R. F. Robinson, 1953: Uranium mineralization in the Sunshine Mine, Idaho. *Min. Eng.* 5:495-511.
- Kerr, P. F., and others, 1956: *Alteration and Uranium Mineralization, Marysvale, Utah*. Geological Society of America (in press).
- 1956: *Collapse Features, Temple Mountain Uranium Area, Utah*. U.S. Atomic Energy Commission (in press).
- Love, J. D., 1952: *Preliminary Report on Uranium Deposits in the Pumpkin Buttes Area, Powder River Basin, Wyoming*. U.S. Geological Survey Circular 176.
- Lovering, T. G., 1955: Progress in radioactive iron oxides investigations. *Econ. Geol.* 50:186-195.
- 1954: Radioactive deposits of Nevada. *U.S. Geol. Survey Bull.* 1009-C.
- Miller, L. J., 1953: *Uranium Ore Controls of the Happy Jack Deposit, White Canyon, San Juan County, Utah*. U.S. Atomic Energy Commission RME-33.
- Mitcham, T. W., and C. G. Evensen, 1955: Uranium ore guides, Monument Valley district, Arizona. *Econ. Geol.* 50:170-176.
- Phair, G., and K. O. Shimamoto, 1952: Hydrothermal uranothorite in fluorite breccias from the Blue Jay Mine, Jamestown, Boulder County, Colorado. *Am. Min.* 37:659-666.
- Weeks, A. D., 1952: *Summary Report on Mineralogic Studies of the Colorado Plateau*. U.S. Geological Survey, TEMR 431.
- Weir, D. B., 1952: *Geologic guides to prospecting for carnotite deposits on Colorado Plateau*. U.S. Geol. Survey Bull. 988-B.



## *Chapter 8*

---

### A SYSTEMATIC METHOD OF EXPLORATION FOR AND EVALUATION OF URANIUM DEPOSITS IN FRANCE \*

---

A method can be recognized as valid only when it has given some proof of its efficiency confirmed by success. It is therefore necessary at the start of a discussion of this method to review briefly the results which have been obtained in the French Union. Nearly nine years have elapsed since the beginning of exploration undertaken by the Direction de Recherches et Exploitations Minières. Now the Commissariat à l'Energie Atomique owns principally in continental France, where the largest effort has been made, such a large number of deposits that France is without any doubt the most important producer of uranium in Western Europe.

This success has been achieved in spite of the fact that until now the activity of the Services de Recherches has been limited to areas considered favorable, that is, granitic massifs, and these are very far from being completely explored. Such a result might have been expected if at the beginning, in 1947, precise data had been available. On the contrary, the program had to be started on the basis of [uranium] occurrences which were not only very small but poorly known and very often misleading.

In fact by the beginning of 1948 it was apparent that none of the occurrences known at the time had any geological or metallogenic significance, and that it was necessary to start from zero and establish a method of exploration and evaluation which would be modified constantly according to experience and would allow us to make as rapidly as possible a general inventory of our uranium resources. For rapid success it was necessary simultaneously (1) to determine geological guides susceptible of variation, according to regions with

\* From Geneva Paper 338, "Méthode de recherches et d'étude des gîtes uranifères" by André Lenoble, Chief of the Mineral Exploration Service of the Commissariat à l'Energie Atomique of France. The text has been edited to some extent and is not a completely literal translation.



different lithologies, structures, etc., (2) to define a tactic adapted to each step of exploration, and (3) to ascertain what equipment was needed for each of the different stages of exploration and to have it manufactured.

The method was originally established for exploration in crystalline massifs, but it will be shown that it is adaptable to the exploration of sedimentary formations in which the geometry of outcrops makes evaluation less difficult than in the case of granite. The irregularity and complicated structure of the latter require a much more detailed and methodical plan.

**The guiding principles applicable to mineralization in crystalline massifs.** The distribution of occurrences which were known in 1947 only on the periphery of the Massif Central indicated that the favorable formations were granite or granulitic granite \* considered of Hercynian age; but at the time there was no precise idea of the role played by structure in the localization and concentration of the primary minerals of uranium.

Very rapidly, and even before the analyses of pitchblende had achieved the desired precision, it was noticed that the role of postgranite tectonics was primary, and of particular importance were structures modified well after the emplacement of the granite. The first discoveries of pitchblende *in situ* (La Crouzille) had shown the significance of this guide to exploration.

Unfortunately, geological maps were lacking in precise information on granite tectonics and it was therefore necessary to resurvey in detailed fashion the geology of those areas of intense fracturing, and especially the edge of the Massif, localizing the survey at first in the zones where occurrences of secondary minerals were known and later extending exploration along the fracture zones. Deposits of uranium are seldom found in veins or veinlets within the large fractures; they are found, instead, nearby, in the zone of secondary faults, with or without breccias and mylonites, and generally oblique to the major breaks.

In fact, all the uraniferous veins or veinlets are localized near the gross structures which have affected the granite masses, either within the granite itself or in the metamorphic rocks around the edge.

This guiding principle is much more important than the mineralogical guides which had been used previously: smoky quartz or even secondary uranium minerals which are observed more and more irregularly distributed, sometimes very remote from the primary deposits and even without any connection with them. Nevertheless, the presence of secondary minerals *in situ* in fracture zones, especially if these minerals are not solely uranium phosphates, is a very significant guide.

A second important principle has been established by a number of observations: the important deposits of uranium are accompanied by a chalcedonic

\* In French usage, acid muscovite granite, generally with automorphic quartz. [Ed.]



gangue rather than quartz, and very frequently by black fluorite mineralization. The chalcedonic gangue is an especially important exploration guide because of its resistance to alteration and erosion.

The reddish coloration of rocks which is exhibited so often in the neighborhood of uraniferous veins permits, when the alteration is not extensive, the localization of these deposits, but is not indicative of uraniferous deposits alone: it is due largely to pyrite, which is, among the mineral associations of French uranium deposits, the only ore constant. The reddened zones caused by unrestricted water circulation often cause radioactivity anomalies which are sometimes related to the uraniferous formations but as often have no connection with a deposit in place. The presence of these reddened zones does not constitute a specific exploration guide for uraniferous deposits.

The same is true for dikes or sills of more basic composition than granite, which were originally considered a nearly imperative guide; yet they could have had a poorly defined physicochemical or purely mechanical effect on mineralizing solutions which encounter them. However, they present some interest because of the exploitable accessory concentrations of secondary minerals which they produce. There is not in all cases any direct genetic relationship between the emplacement of the mineralization and that of the rocks.

Very often there can be added to these very general criteria a series of regional guides which have major importance for the prospector, as for example the localization of mineralization in zones of facies variation. Guides of this type are many and varied. It is only after long study in a particular region that it is possible to show their value.

Special geochemical and geophysical techniques demonstrate the existence of certain guides which unfortunately cannot be used by all prospectors since they require special knowledge and equipment. In particular, the concentration of mineralization seems to occur where zones of different resistivities are in contact. This guide is not restricted, however, to uranium deposits.

In conclusion we can summarize as follows the guiding principles of uranium prospecting in granitic massifs:

1. Tectonic irregularities are of special interest, the most favorable being those which have had recurring movement definitely later than the emplacement of the granitic bodies. But among these, the Hercynian massifs are the only favorable ones, and especially the tectonic zones of their borders.

2. The veins or veinlets are localized not in the major fractures, but in the breccias or mylonites which accompany the secondary fractures.

3. The gangue of vein deposits is essentially chalcedonic and fluoritic.

4. The associated metallic minerals have little variation; among them the most characteristic is pyrite. A few other accessory sulfides accompany the uranium minerals: galena, sphalerite, chalcopryrite, bismuthinite.



**Principles applicable to sedimentary formations.** Experience in this category of deposits is rather limited in spite of the fact that prospecting has been carried out in deposits of very different types—syngenetic sedimentary deposits such as the uraniferous phosphate deposits, and deposits in sedimentary rocks of hydrothermal origin, with pitchblende or with undefined mineral species, such as the uraniferous Stephanian shales and the copper-bearing carboniferous Triassic sandstones.

As far as the first are concerned, there is no well-established guide. Only radioactivity measurements on the outcrops permit the definition of the existence or the extensions of the exploitable zones. For the shales and sandstones with mineralization of hydrothermal origin, stratigraphic, lithologic, and tectonic studies are of first importance, since the mineralization is localized in continental series and unquestionably tied to structural features. In all cases the uranium is intimately associated with the presence of organic matter which has fixed it at the same time as other metals, lead or copper. However, we must admit that one of the certainly important conditions for the concentration of uraniferous mineralization is not known, since this mineralization is fixed preferentially in the shales which are less rich in organic matter than coal beds.

### THE METHOD OF EXPLORATION

**Organization.** Three large groups share the diverse activities of field exploration:

1. Preliminary missions, essentially roving field crews whose duty it is to find in any region new occurrences of uraniferous mineralization. In case of a discovery, they make the determination whether facilities for more elaborate investigation are required.

2. The exploration camps, which are an extension of the preliminary missions, being certain of these missions established to study by trenching, coring, and underground development the occurrences which they have themselves found. These exploration camps are formed by crews stabilized for an indefinite period according to the volume of work to be accomplished—that is, according to the importance of the deposits to be evaluated.

3. Exploration services at the division level, to which is assigned the detailed study of a well-defined area recognized as rich in uraniferous deposits and administratively tied to a mining division. The latter is a grouping of a number of deposits, some of which are already in the exploitation stage, others in the evaluation stage, and still others in the prospecting stage.

**Prospecting technique.** Prospecting can be undertaken in different stages of which the definitions are as follows:

1. *Preliminary prospecting.* Carried out with light equipment and light crews (one geologist and two or three prospectors), its aim is to locate the



occurrences or the radioactive anomalies which will determine the zones worth being explored in detail. The preliminary prospecting is made along profiles, the density of which is greater when the area is more favorable (with networks of 200, 100, or 50 meters). Obviously the profiles are laid out as much as possible normal to the structure, but the prospector must make maximum use of the terrain and must not omit any outcrops or topographical features which are located outside the defined profile and which appear interesting to him.

The only absolute rule in this work, if one does not want to jeopardize chances for success, is the *continuous determination* of radioactivity. For this, a light detector with earphones is used which allows freedom of motion even on very broken terrain. It could not be done without difficulty or great fatigue if visual-reading equipment were used. Measurements in preliminary prospecting do not need to be very precise; they correspond to a qualitative marking of the abnormal activities which indicate the possible existence of a deposit or only of an occurrence. A single prospector may cover one to two square kilometers in one working day, depending on the network he is using.

Aerial prospecting is of the same nature. It is commonly used nowadays and we are using it in the areas where geographical conditions are such that the use of the ordinary methods is quite impossible. But whenever possible we still prefer to prospect in the traditional manner—that is, with a crew on the ground. The cost is higher than by plane, the work takes longer, but the observations are much more detailed, since the prospector has the possibility of observing all the geologic details, collecting samples, etc. Aerial prospecting, in spite of certain advantages, is more mechanical.

For rapidly roughing out an area we are beginning to use counting equipment with recorders mounted on vehicles suited to any terrain, but this is limited to countries like France where the network of communicating roads is close enough to make the method advantageous.

2. *Semisystematic prospecting.* This represents an intermediate step between preliminary prospecting and systematic prospecting which will be discussed later, and is used only where preliminary prospecting has been unable to define with sufficient accuracy the zone to study in systematic prospecting. In this case, more sensitive counters are used, visual and with earphones, and a denser pattern of traverses is used. Small excavations are also made in order to define with greater precision the boundaries of the radioactivity anomalies.

3. *Systematic prospecting.* When the preliminary or semisystematic prospecting has demonstrated the existence of an alignment of abnormal activities indicating the possible presence of a deposit, confirmed if necessary by a few small trenches at the most active places to permit gathering a bit of the mineralization, we then go on to systematic prospecting.

Such prospecting obviously is not used when the rocks are bare nor when



preliminary prospecting has defined the existence of a deposit which can be followed and studied in outcrops. It is on the other hand indispensable in regions where outcrops are frequently masked by overburden. Let us remember that the majority of important deposits are in highly fractured zones and thus strongly altered.

The aim of systematic prospecting is to define by radioactivity measurement the general aspect of the deposit or to define its extension when part of it is already known; the essential work consists of making a radioactivity survey map.

**FIRST STAGE.** The "counter map" on which the activities are shown by isorads is made by plotting on a large-scale topographical map measurements according to a grid the spacing of which is closer when the alignment or importance of the anomalies appears irregular. The scale of the map has to be determined as a function of the precision wanted. Thus scales varying from 1:200 to 1:1000 are used, but the scale of 1:500 is commonest. The measurements of activity are made along the grid every five meters, every two meters, or every meter, according to the situation. As shown by the isoradioactivity lines, the radioactivity values indicate the general direction of the deposit, which corresponds generally to the highest activities. However, it is necessary to interpret these activity maps taking into account the overburden, the topography, etc. In an area of strong relief composed of rocks which are greatly altered, the highest activities of the superficial formations do not correspond to the location of the deposit. The uranium minerals, which are readily soluble, are concentrated downdip in secondary products, sometimes rather remote from the original deposit.

Furthermore, in granitic areas the structure is always very complex, forming a network of faults which cut the deposit whether the faults are contemporary or later than the formation of the deposit. These faults present many avenues by which the secondary mineralization is dispersed and they destroy the symmetry of the counter map, making it sometimes very difficult to interpret.

The measurements of radioactivity are made with counters specially constructed for this work and able to indicate approximately the uranium content of the surface rocks, thus providing a preliminary estimate of the potential richness of the deposit.

**SECOND STAGE: SMALL SURFACE EXCAVATIONS.** When the counter map has furnished all the desired data on the configuration of a mineralized zone, trenching is begun in order to (a) confirm the existence of deposition at points of maximum activity, (b) define its geometry—dip and strike—which will be required in future work, particularly drilling, (c) permit the collection of samples from rocks *in situ* in order to study the mineralization and to estimate the grade of the surface zone, (d) define the pattern of the faults which displace the deposits.



These trenches must provide all the geologic and mineralogic data needed to make an estimate of the value of the deposit and to justify the continuation of work.

The choice of location of the trenches, their depth, etc., are not of great importance, but it is important to insist on the construction of a very detailed geologic map (generally made to a scale of 1:50) of the sides of each of the trenches. On this must be noted with the greatest care the mineralized areas, even the most minute fractures, and the location of the samples taken.

The systematic prospecting stage completes the surface work, and from the data obtained we proceed to plan subsurface exploration—drilling and underground development. With it is ended, in principle at least, the work of the preliminary missions as well as of the exploration camps.

**Drilling.** If the results of the prospecting stage are favorable from the geologic and mining point of view, the next step is to extend the information obtained at the surface to various levels in depth, first by drilling and then by underground work if the results of drilling confirm the first indications. This is the usual technique of all exploration. There is only one innovation in the case of uranium exploration: the use of special probes which record the radioactivity and permit an approximate estimation of the richness of the deposit.

In the evaluation of uranium deposits, gamma logging is an essential operation, since in spite of all the care and technical precautions taken, core recovery is nearly always poor because of the nature of the rocks in which the deposits are usually found.

All the information furnished by drilling on the petrography, structure, mineralogy, and radioactivity, as well as the engineering data such as core recovery, are indicated on graphs which show the exact position of maximum radioactivity as well as the value in counts per second, which by experience permits an estimate of the grade.

The study of the characteristics of the radioactivity curve is of major importance. It gives an idea of the distribution of the mineralization. For example, a succession of peaks, each very strong, indicates dispersed mineralization, which in the end will give an average grade lower than that of an activity curve not so high but more regular throughout the intersection of the formation.

When core recovery is good (as happens only in homogeneous sedimentary formations) core samples are used for evaluating the grade, the cores being split lengthwise. Vein deposits are too irregular (breccias, siliceous zones, clay alteration, fragile mineralization) to permit such an operation and we must rely on the gamma logs.

**Underground exploration.** All the various preceding operations having shown the existence of a deposit, the geometry of which has been defined by drilling and the approximate average grade estimated by gamma logging, it



remains to determine the exact grade, the characteristics, and the distribution of mineralization, to establish the paragenesis, and to define minimum reserves.

It is necessary, in order to obtain precise data on all these points, to proceed with underground development to a certain level to be chosen deeper than the weathered zone. The drilling program must have provided information on this point.

It is never desirable to plan underground work to a depth of less than 30 meters. The excavations must be situated definitely below the zone of oxidation to obtain precise information on the type of mineralization, information which will not only be necessary for defining the importance of the deposit from a mineralogical point of view, paragenesis, etc., but will also permit evaluation from the point of view of the mechanical or chemical treatment of the ore. Further, this work must furnish all the information that will be necessary to the miner (condition of the ground, etc.).

In general, the exploratory mining work is done by means of shafts 40 to 50 meters deep or by adits, when the relief is suitable, from which drifts are driven in the mineralized zone; if this zone is very thick, the work is completed by cross cuts to the edges and by horizontal drilling and gamma logging. In order to estimate as accurately as possible the minimum indicated tonnage, raises are made to the surface. During excavation sampling is done using different methods depending on the situation; but in vein deposits of uranium, where the distribution of the mineralization is irregular, it is preferable to use extensive channel sampling.

Measurements of activity are made at the same time, generally in the center of the working, to obtain an average radioactivity.

With each round, the geologic and mineralogic details of the advancing face are surveyed in great detail and the radioactivity is measured at every point. As soon as the exploratory mining work has supplied all the significant data desired on the mineralization, the grade, and the extent of the deposit and defined a minimum reserve which will permit a conclusion as to its exploitability, the work of the exploration staff ends as far as prospecting is concerned. Later on, during the mine-development stage, the exploration staff is responsible for direction of the mining of the deposit by the study of the geology, and for evaluation of reserves. Detailed surveys and sampling are therefore continued in the same manner as during the exploratory work.

**Conclusion.** This method of evaluation and exploration of uranium deposits may appear cumbersome and complicated. However, experience has shown that there are very few cases where one can dispense with any of these operations. Moreover, results prove that this method provides about all the certainty necessary to a reliable judgment of the value of continuing the work as each different stage is complete. Nothing is as costly as incomplete or poorly done prospecting.



# *Chapter 9*

---

## RADIOMETRIC PROSPECTING \*

---

The steadily increasing demand for radioactive raw materials has stimulated the rapid development of radiation detection instruments and techniques for measuring radioactivity in the field. A large variety of instruments are now commercially available, ranging from simple Geiger-Müller counter detectors obtainable at low cost to highly precise and sensitive instruments costing many thousands of dollars. The older techniques of measurement have been refined, and newer techniques based on instruments mounted in aircraft and automobiles have been developed.

The radioactivity characteristic of uranium- and thorium-bearing materials offers a unique means of direct detection of significant concentrations of these elements. Unfortunately, even the most penetrating gamma radiation from radioactive materials is effectively absorbed by a few inches of intervening materials. Radioactivity measurements, whether at the outcrop, in drill holes, or in mine openings, will detect only those radioactive materials exposed at a surface or concealed by a small amount of other materials.

It is now commonplace for prospectors, mining engineers, and geologists to carry radiation detection instruments, both those actively engaged in the search for radioactive materials and those searching for other ores. Using sensitive radiation detectors, uranium prospectors need not be able to identify radioactive minerals nor have more than a cursory knowledge of geology; a marked increase in radioactivity indicates where further work should be done.

### TYPES OF INSTRUMENTS

The principal instruments now used to prospect for radioactive raw materials are the Geiger-Müller counter and the more recently developed scintillation

\* The first three sections of this chapter are from Geneva Conference Paper 511, "Instruments and Techniques for Measuring Radioactivity in the Field" by F. W. Stead, U.S. Geological Survey. Selected references are listed alphabetically at the end of the chapter.



counter. From a relatively crude and cumbersome device, the portable Geiger-Müller counter has been developed by the health physicists in the atomic-energy program into a lightweight, rugged, and highly reliable instrument. Primarily this instrument was developed and is used for monitoring the radiation intensities in laboratories and manufacturing plants handling high concentrations of radioisotopes. Secondly the instrument is widely used to prospect for uranium, and probably more portable Geiger counters are in use today than all other geophysical instruments. The portable scintillation counter, because of its greater sensitivity, is more useful than the Geiger-Müller counter in areas of low radiation intensity, particularly at or near the level of background radiation.

The Geiger-Müller counter tube has remained fundamentally unchanged since first developed by Geiger and Müller. Most counter tubes used in portable instruments have thin-walled glass or aluminum cathodes that will admit the more energetic beta radiation in addition to gamma radiation. Counter tubes with bismuth cathodes or with multiple cathode-anode construction to increase the efficiency of gamma-ray detection are used in some portable instruments.

The present-day scintillation counter is essentially a phosphor viewed by an electron-multiplier phototube. Almost all portable gamma-ray scintillation instruments use thallium-activated sodium iodide crystals as the phosphor. Semiportable instruments installed in aircraft and automobiles occasionally use large plastic phosphors, and experimentally, large-volume liquid scintillators.

The portable scintillation counter has several advantages over the Geiger-Müller counter: (1) higher efficiency for gamma-ray detection, (2) lower relative cosmic-ray background because of the higher gamma-ray efficiency, and (3) relatively short resolving time, allowing higher counting rates without serious coincidence loss. Comparative disadvantages of the scintillation counter are (1) present high cost and scarcity of large thallium-activated sodium iodide crystals, (2) small pulse output from the photomultiplier, requiring a better amplifier circuit than for the Geiger-Müller counter tube, and (3) a high-voltage regulation for the photomultiplier which is far more critical than regulation for the Geiger-Müller counter tube. In small, lightweight portable instruments, adequate high-voltage regulation is difficult to achieve.

The amplifier circuits used in portable equipment to count the random pulses from radiation detectors are mainly counting-rate meters, and to a very limited extent, scalars. A large variety of counting-rate meters have been used, all involving pulse shaping to uniform size followed by integration into a direct current which is recorded by either a visual or a graphic meter. Initial development of a "total-intensity" rather than a pulse counting-rate meter for scintillation detectors has been completed; as yet, insufficient development and testing of this amplifier have been done to determine its applicability in portable



instruments. Scaling circuits for portable instruments have been developed from the basic scale-of-two circuit; portable scale-of-eight instruments are electronically limited to low counting-rate applications.

Most portable instruments of the counting-rate meter type are relatively stable and reliable and do not exhibit marked variations in response because of temperature change, decrease in battery voltage, or shifting detector sensitivity. Simple direct-indicating instruments, in which a pulse is recorded as a click in earphones or as the flash of a neon bulb, are now rarely used because of their limitation to low counting rates. Semiportable instruments, where size and weight are not limiting factors, are designed to use laboratory-type amplifiers and recorders.

### FIELD TECHNIQUES

Essentially all field techniques are based on the detection of gamma radiation. Supplemental detection of beta radiation is useful in picking out the highly radioactive rock and mineral fragments from mineralized outcrops, and many portable Geiger counters are designed to be both beta and gamma sensitive. Because of the short range of alpha radiation, its detection has not proved to be practical in the field.

As commonly used in prospecting for uranium, field techniques of measurement are essentially qualitative. A moderate increase in radioactivity has long been considered sufficient evidence to collect samples or to file a mining claim. To have semiquantitative significance, field techniques of measurement must be applied with a clear understanding of the many factors involved. These factors include the background component of measurement, the solid-angle or mass effect, the absorption and scattering of radiation by various media, radioactive equilibrium in natural materials, and natural and artificial contamination. Simple relationships cannot be established among these factors, and considerable experience is usually necessary for proper interpretation of field measurements.

Valid semiquantitative interpretation of field measurements requires that the radiation detection instruments should be standardized and calibrated at all times. Standardization involves testing the instrument response with a moderately strong radioactive standard. To be satisfactory for extended use, a portable field instrument should reproduce the measurement of the standard within a stated amount, commonly 10%.

### CALIBRATION

Calibration in absolute units is usually based on first flight, or direct, quanta from a radium source, and is then expressed as milliroentgens per hour. The-



oretically, if all portable Geiger and scintillation instruments are correctly calibrated in terms of milliroentgens per hour, measurements made with different instruments should be directly comparable, provided that the spectral energy distribution of the gamma radiation measured is effectively the same as from radium. Practically, several difficulties arise in the large-scale quantitative calibration of instruments. Gamma radiation from natural sources is always much scattered, so that the effective energy spectrum is greatly enriched on the low-energy end. Instruments calibrated with first-flight quanta from a point radium source will not show the correct intensity in milliroentgens per hour when the measured radiation is partly scattered. The gross readings will still be comparable from counter to counter of the same energy response, but units such as milliroentgens per hour are essentially meaningless in field practice, where many instruments of different types may be used. Specific difficulties in calibration are (1) the different response of the Geiger and scintillation counters to various energy levels of gamma radiation, particularly since the scintillation counter has good sensitivity for very low energies and the Geiger counter does not, (2) the variation in electron-multiplier phototubes and the consequent variation in sensitivity of scintillation counters, and (3) the nonlinearity of the amplifier circuits in portable instruments at high counting rates.

Other units, such as counts per minute or multiples of background radiation, have been used to calibrate instrument response. In most cases these units indicate a standardization of response, not a calibration in the absolute sense. Measurements expressed in counts per minute are meaningless except for instruments of essentially identical response characteristics and for similar geometry of measurement. Multiples of background are useful for distinguishing significant variations of radioactivity within a limited area, but because the regional background radiation varies from area to area, multiples of background are not directly comparable unless expressed in absolute units.

The most useful calibration would be in absolute units for the principal element sought, uranium: that is, the calibration would be based on measurements of the radiation intensity from materials containing a known amount of uranium oxide in equilibrium with the disintegration products. The calibration would then be expressed as per cent equivalent uranium oxide. Some individual instruments have been so calibrated. Where adequate consideration has been given to the factors affecting the interpretation of measurement, individual instruments have provided measurements of the uranium content accurate to within a few thousandths of a per cent. The same difficulties in large-scale calibration arise as in the use of microroentgens per hour, and no major effort has been made to calibrate the response of portable instruments in terms of equivalent uranium, equivalent thorium, or equivalent potassium.

Almost all portable instruments now used by government agencies are



calibrated in milli- or microrentgens per hour using gamma radiation from a point radium source. Although such calibration is not entirely satisfactory for field measurements of radioactivity, it is the easiest to use and is the best compromise among other possible means of calibration. Measurements in milliroentgens per hour, made in widely separated areas with instruments of different types, can be roughly correlated, particularly where the general nature of divergence in response among the instruments is known.

Because of the large variety of portable instruments now available, instruments can be selected that are statistically adequate over the anticipated range of measurement. Statistical uncertainty introduced by very low counting rates is seldom a factor of importance in present-day measurements.

#### DEVELOPMENTS IN RADIOMETRIC INSTRUMENT CIRCUITS \*

In the United Kingdom designs of radiometric prospecting instruments have been based, to a very large extent, on the use of a special type of Geiger counter known as the "halogen-quenched type," which is characterized by extreme ruggedness and almost infinite life.

Cold-cathode trigger valves,<sup>†</sup> or more recently, transistors have generally been chosen in preference to hot-cathode valves for use in the trigger and ratemeter circuits. The latter are much less economical of battery power, owing to the heating required for cathodes, and also the fact that in general at least one valve in the circuit operates with appreciable standing anode current. In addition, under the arduous conditions of use in the field, cold-cathode valves have tended to prove more reliable, and it seems likely that transistors also will show an advantage in this direction, though there has been insufficient field experience so far to confirm this.

Figure 9.1 shows a typical cold-cathode trigger and ratemeter circuit, as used with a Geiger counter. The anode-cathode gap of the valve normally passes no current, but a small "keep alive" current of  $10^{-8}$  to  $10^{-6}$  amp, depending on the type of valve, is fed via the resistor  $R_3$  into the trigger-electrode-cathode gap. This current, which is insufficient to cause breakdown of the main anode-cathode gap, serves the dual purpose of keeping the trigger electrode at the correct voltage for breakdown and of maintaining sufficient ionization in the valve so that breakdown can occur rapidly on the application of a triggering pulse. When the Geiger-counter tube produces a pulse, it causes a momentary increase in this "keep alive" current, which causes, in turn, breakdown of the anode-cathode gap of the valve. Capacitor  $C_2$  then discharges through the valve until the voltage across it has fallen to a value equal to the valve's

\* From Geneva Conference Paper 763, "Instrumental Developments in the Prospecting, Mining, and Chemical Processing of Nuclear Materials" by H. Bisby, E. Franklin, and D. Taylor, Atomic Energy Research Establishment, Harwell, England.

<sup>†</sup> Vacuum tubes. [Ed.]



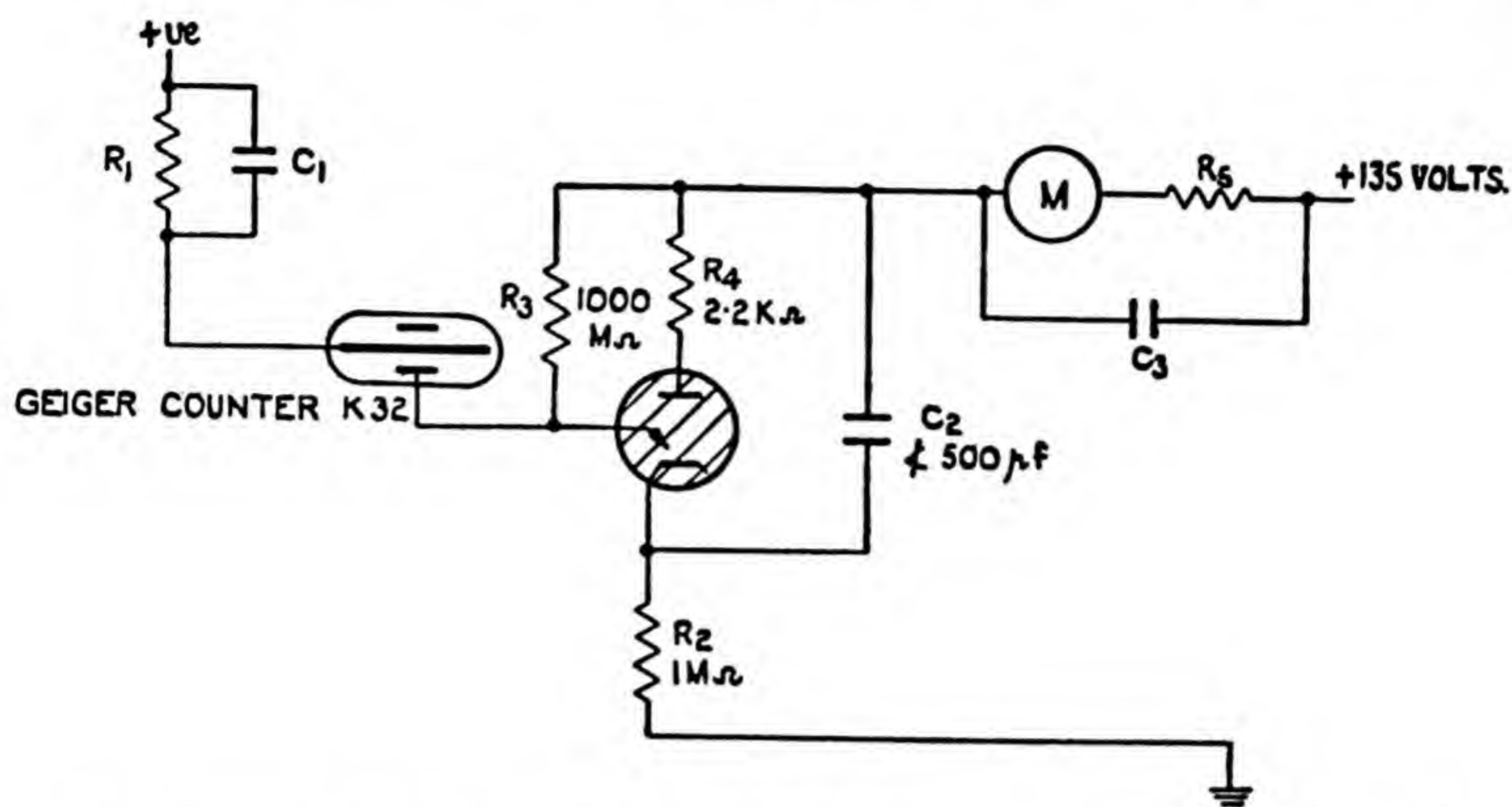


FIG. 9.1. A cold-cathode valve trigger and ratemeter circuit used with a Geiger counter.

extinction voltage. Since the resistor  $R_2$  is chosen so that the current which can flow through it is too small to maintain the anode-cathode discharge, the latter then extinguishes, and  $C_2$  commences to recharge through  $R_2$  to its original voltage. The cathode potential of the valve therefore rises rapidly when the discharge is triggered and falls exponentially towards earth with a time constant  $C_2 R_2$  after extinction of the discharge. At some point during the fall, the potential across the trigger-electrode-cathode gap reaches the breakdown value and the "keep alive" current is re-established. Resistor  $R_4$  is inserted to limit the peak discharge current through the valve, and the combination  $R_1$  and  $C_1$  serves to limit the discharge pulses of the Geiger counter.

It has been seen that each pulse from the Geiger counter causes a discharge of capacitor  $C_2$  from the high-tension supply voltage down to the extinction voltage of the valve, and the recharge current is taken from the power supply. The mean current taken from the power supply is therefore proportional to the Geiger tube mean counting rate, and a measure of the latter is therefore obtained by inserting a current meter  $M$  in series with the power supply. Capacitor  $C_3$  and resistor  $R_5$  serve to integrate the pulsating current over a sufficiently long period to reduce the meter fluctuations to an acceptable value.

Figure 9.2 shows a similar circuit in which the radiation detector is a scintillation counter and the cold-cathode valve is a four-electrode valve. In this valve (the "keep alive"), current flows between the trigger electrode (3) and the auxiliary cathode (2)—the main discharge, when triggered, being between anode (4) and cathode (1). Triggering is accomplished by means of either a negative pulse on the auxiliary cathode, or a positive pulse on the trigger electrode.

These simple circuits have been used successfully in portable, transportable, and installed equipment. One equipment designed for car-borne survey work



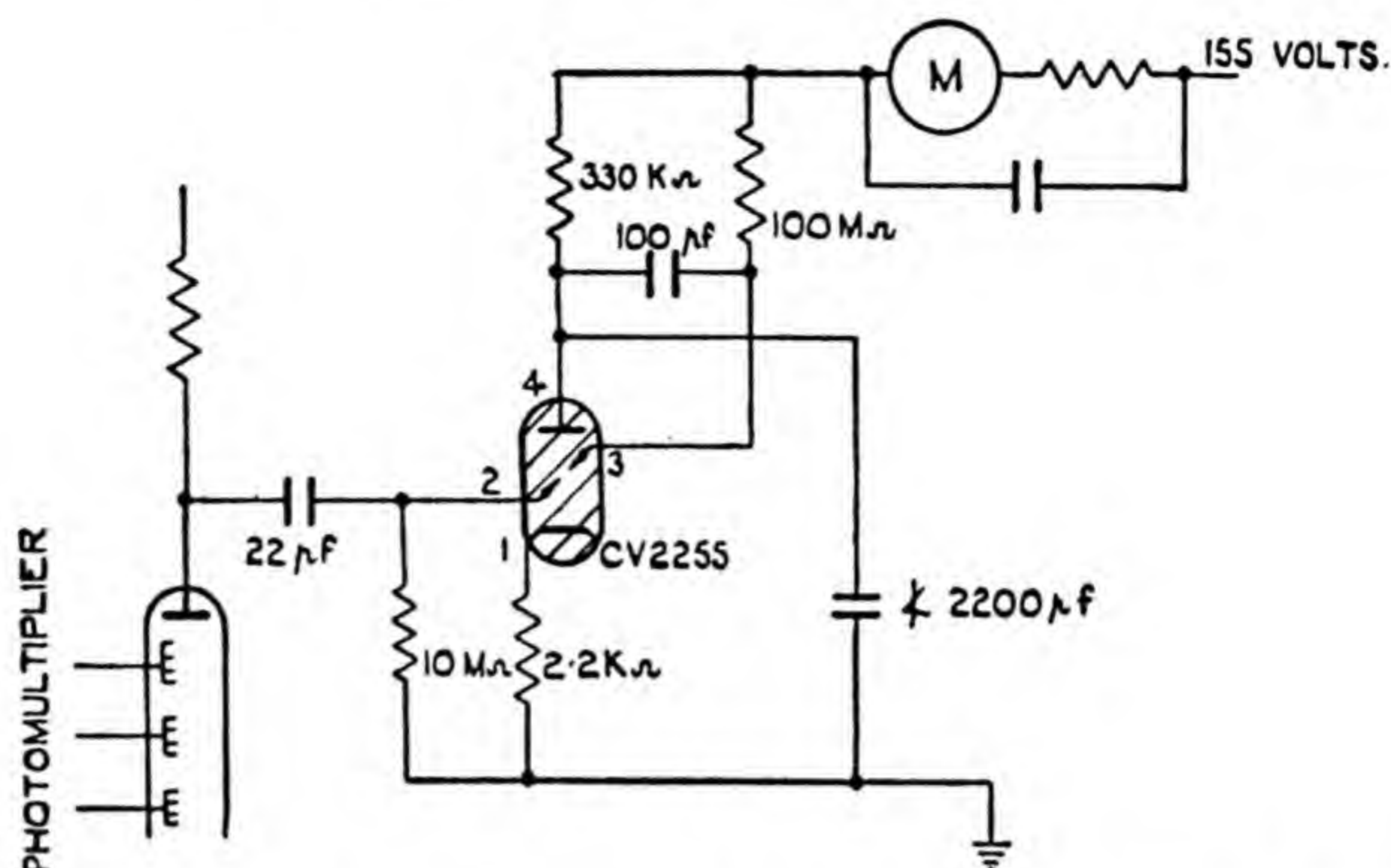


FIG. 9.2. A cold-cathode valve trigger and ratemeter circuit used with a scintillation counter.

consists merely of the circuit of Figure 9.2 together with a power-supply circuit and a 0–50 microamp chart recorder which is inserted in series with meter M. The use of the high-sensitivity spark recorder, which is described below, avoids the necessity of having current amplifiers.

Figure 9.3 shows the circuit of Figure 9.1 rearranged for gamma-ray logging of deep boreholes. The use of the cold-cathode valve makes it possible to employ a single-core cable from the underground probe to the surface instrument, without the use of a filament battery in the probe, or complicated supply circuits. The trigger and ratemeter circuits of the underground probe are as in Figures 9.1 and 9.2, except that the meter is coupled into the circuit in a different manner. The current pulses of the trigger valve  $V_1$  are passed via the transformer  $T_1$  and the cable into a “diode pump” circuit consisting of

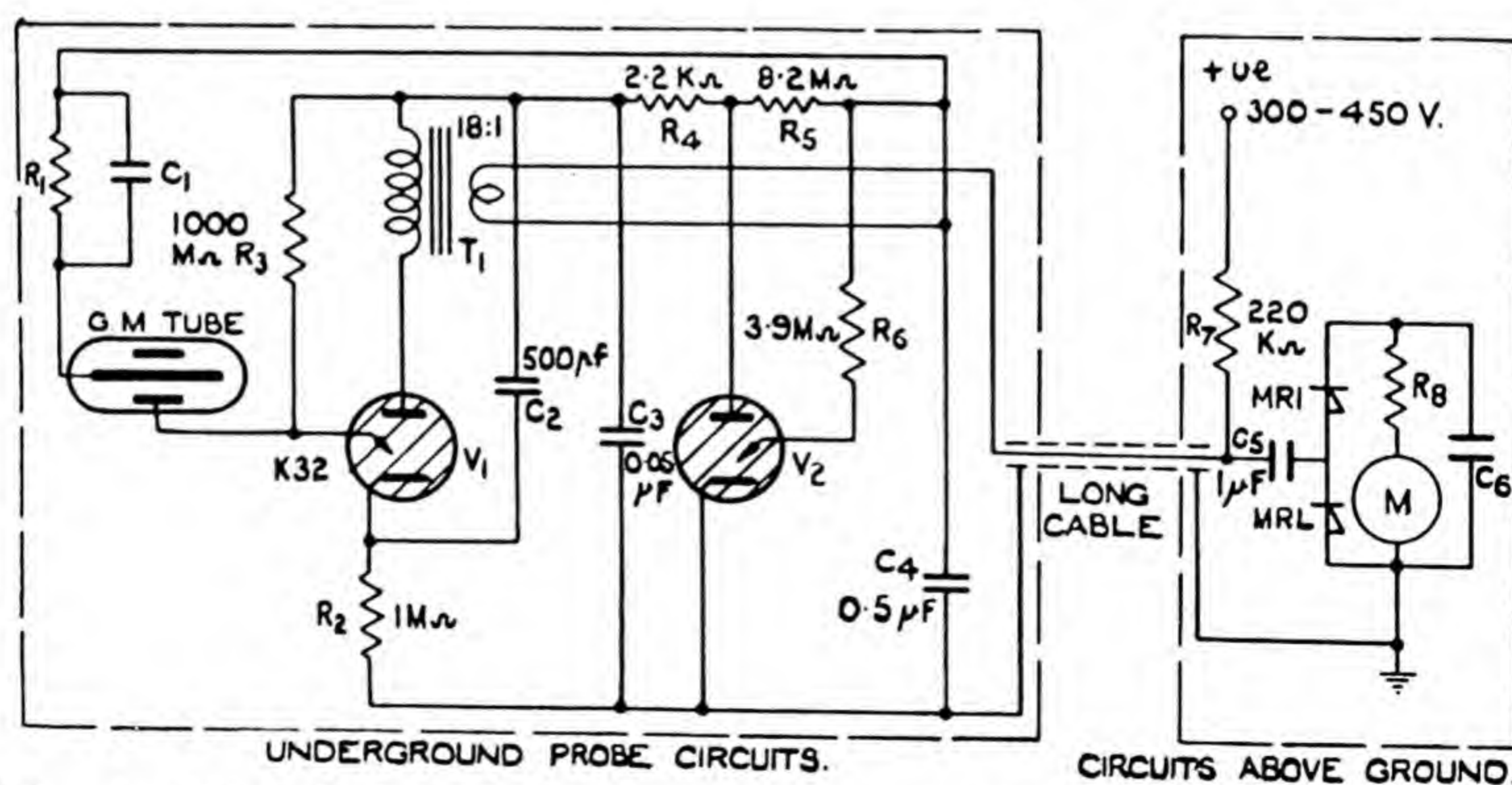


FIG. 9.3. A cold-cathode valve trigger and ratemeter circuit arranged for borehole logging.



capacitor  $C_5$  and rectifiers MRI and MRL, and the meter measures the rectified current. The same cable conductors carry current down to the probe at the voltage required by the G.M. tube, the latter obtaining its supply via the pulse transformer secondary winding. Capacitor  $C_4$  decouples the transformer pulses from the G.M. tube. Current passing from the G.M. tube supply through resistor  $R_5$  operates the voltage stabilizing valve  $V_2$  and supplies the necessary operating voltage (135 volts) for the trigger valve  $V_1$ .

The circuits of Figures 9.1 and 9.2 are attractive for portable instruments because they can be made extremely economical of battery power. It has been adopted as more or less standard practice, on the grounds of robustness, that no meters of greater sensitivity than 0–50 microamperes shall be used in portable or transportable equipment. However, by the use of current transformers it has been found possible to design a satisfactory multirange trigger and ratemeter circuit taking a total power of only 2 milliwatts. Since this is comparable with the power taken by the Geiger counter itself, there is little to be gained in over-all power economy by the use of junction-type transistors. Point-type transistors show a distinct disadvantage in this direction (10–15 milliwatts) if the circuit is designed to operate up to the temperature limit of  $60^\circ\text{C}$  which is usually specified, owing to the much higher value of standing collector current with zero emitter current.

However, transistor circuits are gradually replacing cold-cathode trigger valve circuits in most applications because they give greater flexibility of design. The most serious limitations of the cold-cathode valve arise from the measures which have to be taken to ensure correct and permanent extinction of the anode-cathode discharge when the capacitor potential has fallen to the extinction value. If continuous discharge or multiple discharges are to be avoided, each of the components  $C_2$  and  $R_2$  (Fig. 9.1) must have a certain minimum value, depending on the type of valve. This sets a limit to the mean current which can be drawn from the valve, and also to the maximum frequency at which it can be triggered, the latter being the more serious limitation. If a fairly linear calibration of meter reading against Geiger-counter counting rate is required, no existing types of valve which are suitable for use in instruments of this type can be operated at mean frequencies higher than about 300 counts per second.

In the heavily conducting state, the collector-base voltage drop is much greater in the point-type transistor than in the junction type; and for stable operation in trigger and ratemeter circuits, the former type therefore requires a higher operating voltage. This, together with the much greater power consumption already mentioned, makes the point type much less attractive than the junction type.

Figure 9.4 shows a typical junction transistor trigger and ratemeter circuit triggered from a Geiger counter. The trigger circuit is essentially a grounded



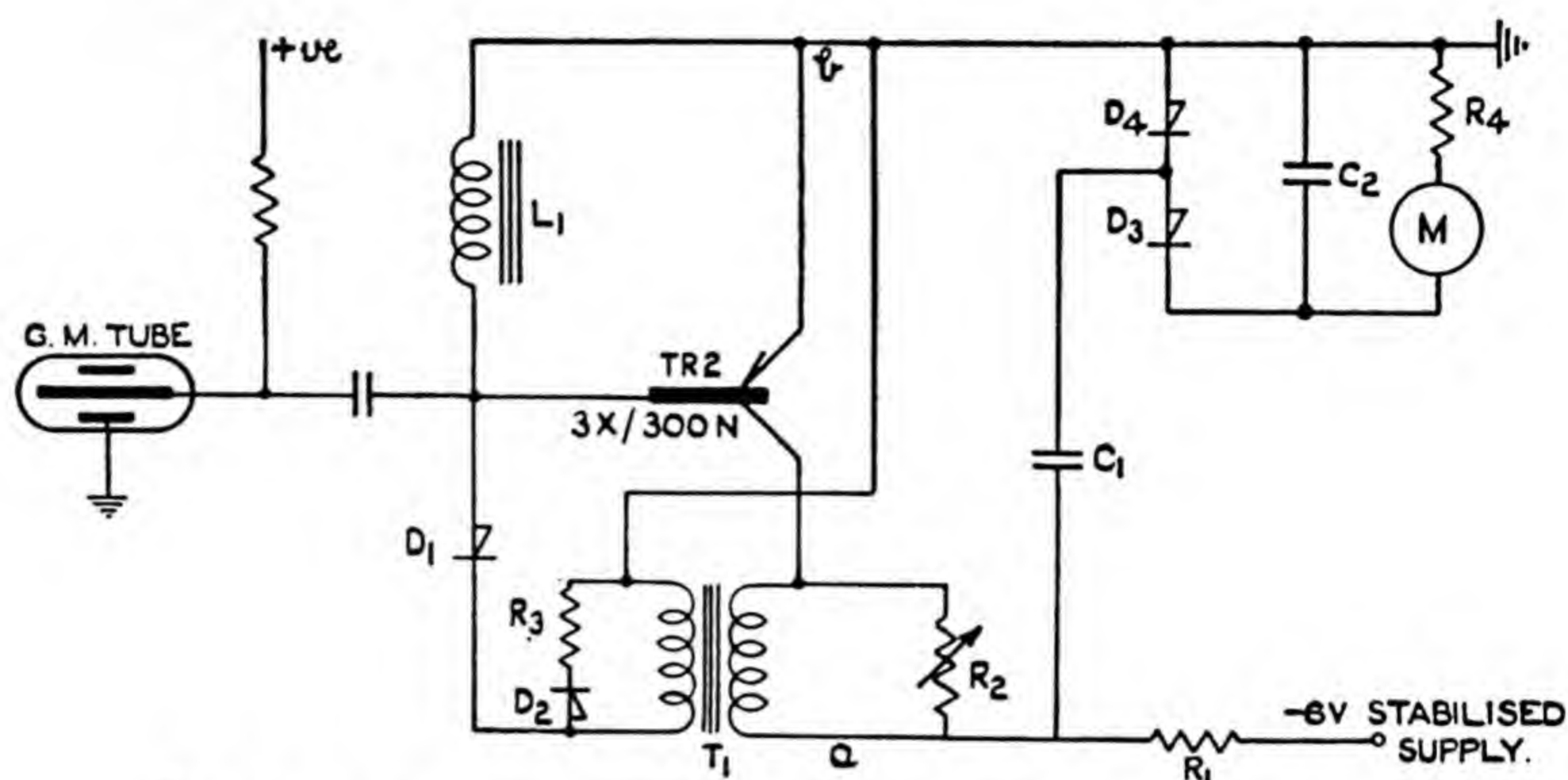


FIG. 9.4. Junction transistor trigger and ratemeter circuit.

emitter amplifier with positive feedback via the transformer from collector to base of the transistor. The base and emitter of the transistor are short-circuited, as far as D.C. conditions are concerned, by the choke  $L_1$ , in order to keep the standing collector current down to the minimum. In between pulses, therefore, the emitter-base current is zero and the collector current is only a few microamperes. When a sufficiently large negative pulse is applied to the base from the Geiger counter, the emitter begins to take current, therefore turning on the collector and making the base heavily negative. Practically the whole of the voltage between points *a* and *b* then appears across the collector winding of the transformer, and the emitter current is determined by this voltage, the transformer ratio, and the emitter-base circuit resistance. The transistor remains in this turned-on state until the transforming magnetizing current has risen to a value equal to the emitter current multiplied by the transistor current gain. No further increase beyond this is possible, and so the transformer voltage collapses, the emitter current ceases, and the transistor turns off.

By suitable circuit design it is possible to ensure that well before the transistor turns off, the potential between points *a* and *b* has fallen to a small fraction of the 6 volts of the stabilized supply. The amplitude of wave form at *a* is therefore well defined, and the "diode pump" circuit consisting of capacitor  $C_1$  and rectifiers  $D_3$  and  $D_4$  give a rectified current in the meter *M* which is proportional to the rate at which triggering occurs and also to the value of  $C_1$ . Rectifier  $D_2$  prevents self-oscillation of the circuit due to "ringing" of the transformer, and the silicon rectifier  $D_1$  stabilizes the triggering sensitivity of the circuit by providing a nonlinear resistance in the feedback loop which does not vary seriously with temperature.

This basic circuit is being used in many types of equipment, including bore-hole logging instruments. In the latter case, where a Geiger counter is used



the underground probe becomes very simple, since the trigger circuit can be kept aboveground. The probe contains merely a Geiger counter with its discharge-limiting capacitor and resistor, a pulse transformer to match the counter into the cable, and a condenser to decouple the pulse circuits from the G.M. tube power supply. A single concentric cable is used as in Figure 9.3.

Permanent records can again be obtained without further power amplification by using a 0–50 microamp spark recorder.

A part of the specification of prospecting equipment for general use is that it shall operate satisfactorily over the temperature range  $-20^{\circ}\text{C}$  to  $+60^{\circ}\text{C}$ . The circuit of Figure 9.4 shows some change of triggering sensitivity over this range, but this is not sufficient to give trouble in Geiger counter instruments. However, in scintillation counter instruments, where high stability of triggering sensitivity is essential, it has been found necessary to stabilize the sensitivity of the trigger circuit itself at a low value by the application of a positive bias voltage of about 1.5 volts to the base of the transistor and to recover the high over-all sensitivity by means of a two-stage transformer-coupled transistor amplifier between the photomultiplier and the trigger circuit.

Transistors are also finding application in the power supplies of instruments of the type discussed above. Figure 9.5 shows a typical power-supply circuit for a portable instrument.

It has not been found satisfactory to use ink recorders in transportable equipment. Two types of electrical recording have generally been used. One uses Teledeltos facsimile paper, and the pen, to which a potential of about

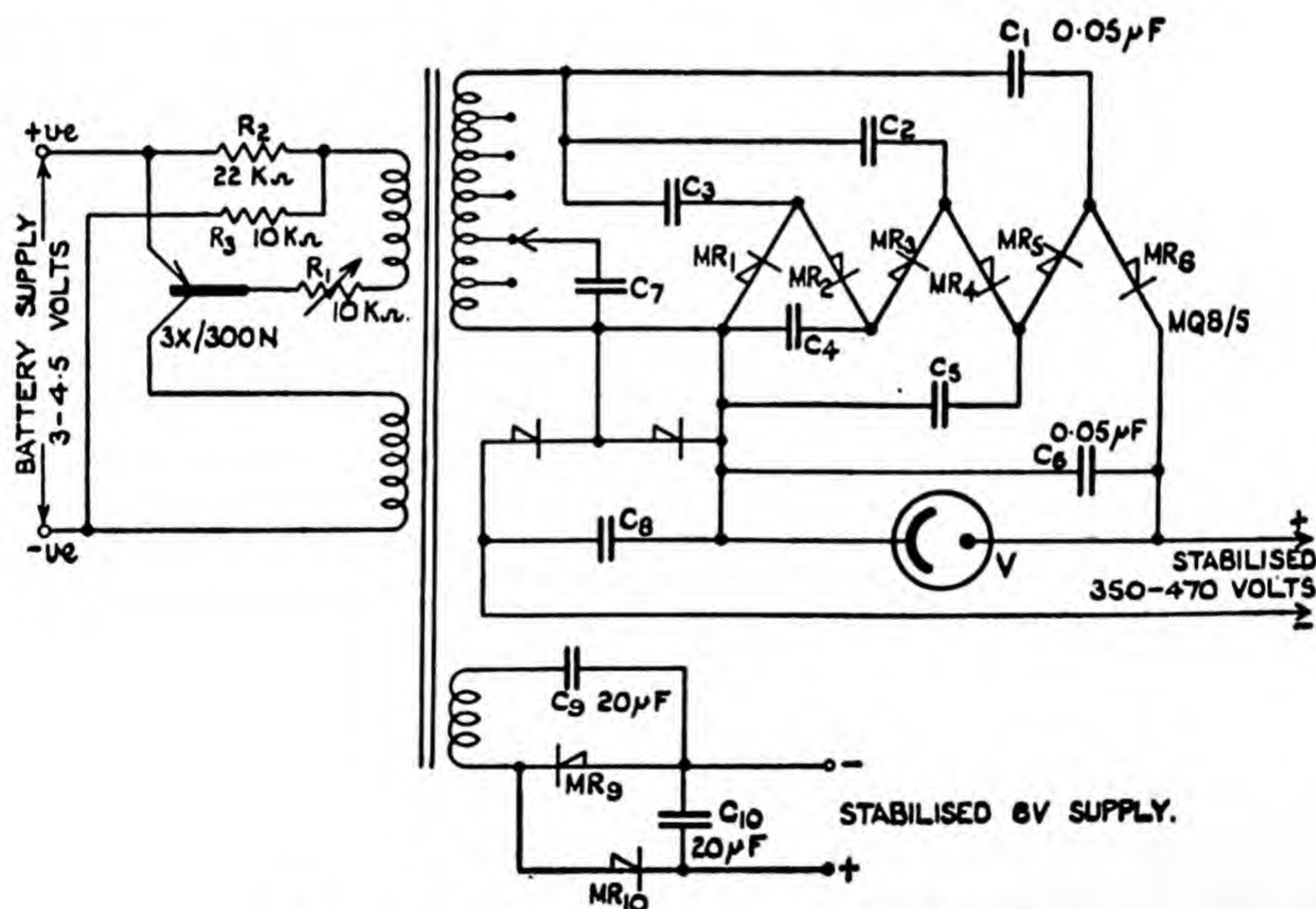


FIG. 9.5. Transistor power supply circuit.



300 volts is applied, is a wire contact which touches the paper. In the other type a heat-sensitive paper is used, and the marking is applied by a series of electrical sparks passed between the earthed pen and a strip of metal under the paper, which is pulsed from an ordinary motor-car ignition coil and contact breaker. The latter type has the great advantage that the pen does not touch the paper and therefore sensitive meter movements can be used. This avoids the necessity for current amplification. When using the former type of recorder, current amplification has been obtained using a magnetic amplifier or an arc discharge valve.

## SELECTED REFERENCES FOR CHAPTER 9

- Birks, J. B., 1953: *Scintillation Counters*. New York, McGraw-Hill Book Company, Inc., and London, Pergamon Press.
- Buck, W. L., and R. K. Swank, 1953: Preparation and performance of efficient plastic scintillators. *Nucleonics* 11(11):48-52.
- Davis, F. J., 1954: Scintillation counters. In H. Faul (Ed.), *Nuclear Geology*. New York, John Wiley & Sons, Inc., pp. 31-35.
- Harrison, F. B., C. L. Cowan, and F. Reines, 1954: Large-volume liquid scintillators: their applications. *Nucleonics* 12(3):44-47.
- Johnson, D. H., 1954: Radiometric prospecting and assaying. In H. Faul (Ed.), *Nuclear Geology*. New York, John Wiley & Sons, Inc.
- LeVine, H. D., 1954: Logarithmic DC ratemeters for scintillation counters. *Nucleonics* 12(2):36-39.
- Linden, B. B., 1954: New photomultipliers and operating data. *Nucleonics* 12(3):20-23.
- Swank, R. K., 1954: Recent advances in theory of scintillation phosphors. *Nucleonics* 12(3):14-19.
- Wilson, E. E., V. C. Rhoden, W. W. Vaughn, and H. Faul, 1954: *Portable Scintillation Counters for Geologic Use*. U.S. Geological Survey Circular 353.
- Wouters, L., 1954: Production of plastic phosphors in quantity. *Nucleonics* 12(3):26.



# *Chapter 10*

---

## SURFACE RADIOMETRIC TECHNIQUES

---

---

\* Surface techniques include local surveys or spot examinations, detailed surveys, and regional surveys. The application of surface techniques, when combined with geologic appraisal and evaluation, has been generally described as reconnaissance for radioactive raw materials.

### TYPES OF SURFACE SURVEYS \*

**Local surveys.** Local surveys, also termed "spot examinations" or "prospecting," are planned either to find localities of anomalously high radioactivity or to evaluate reported occurrences of radioactive raw materials. Such surveys are normally done on foot and are guided by rock types, mineralized zones, and mineral assemblages favorable for the occurrence of radioactive materials.

To indicate possible economic concentrations of radioactive materials a radioactivity anomaly must show at least a several-fold increase over the local background gamma radiation. The minimum increase is frequently considered to be fourfold for measurements made with a portable Geiger counter and twentyfold for measurements made with a scintillation counter. Multiples of the background radiation are occasionally used to define geological groupings of anomalies in an area.

In evaluating an outcrop or a new mine development, a beta-gamma-sensitive Geiger counter is frequently used to scan the outcrop or mine face and thus to select the most radioactive rock and mineral samples for identification and analysis. Using standardized and calibrated detection instruments such as portable scalers, the equivalent uranium oxide content of rock and mineral samples can be determined in the field within plus or minus 0.002%.

**Detailed surveys.** Detailed surveys are made to determine accurately the distribution of radioactivity within an area ranging from a few thousand square

\* From Geneva Conference Paper 511, "Instruments and Techniques for Measuring Radioactivity in the Field" by F. W. Stead, U.S. Geological Survey.



feet to many square miles. The objectives may be specific, such as locating and evaluating radioactive ore deposits, or may be general, such as locating fissures, veins, and other structures or determining the variation of radioactivity in and among rock types. In contrast to local surveys where qualitative measurements of radioactivity with simple portable instruments are frequently sufficient, detailed surveys require semiquantitative measurements made with standardized and calibrated instruments.

Detailed surveys, accurately located in respect to topography and geology, are usually made either on a grid pattern or along widely spaced traverse lines. The measurements are either shown as point values or are compiled as isoradioactivity contours. As an aid in geologic mapping, detailed radioactivity surveys have proved useful in tracing fissures, sills, and dikes, particularly where such features are concealed by talus or residual soils.

In general, little if any correlation can be demonstrated between small radioactive ore bodies at shallow depth and the surface distribution of radioactivity. Occasionally, a closely spaced survey may assist in guiding exploration for concealed deposits. One particular scintillation-counter survey in the Black Hills of South Dakota outlined all known uranium deposits within the 10-microroentgen-per-hour contour interval, where the background radiation intensity was 7 microroentgens per hour. The 20-microroentgen contour, roughly three times the regional background radiation, outlined small areas within which additional deposits were later discovered by drilling. These deposits were as much as 60 feet below the surface. Obviously, gamma radiation from the uranium ore could not penetrate 50 or more feet of rock; uranium or some of its disintegration products must have migrated from the ore to the surface. The application of detailed radioactivity surveying to the search for concealed deposits has been demonstrated to be valuable; however, such application is restricted to a few geologic environments where migration of uranium and its disintegration products is either known or likely to occur.

**Regional surveys.** Regional surveys, usually covering several thousand square miles, have been successful in locating radioactivity anomalies for more detailed investigations and in providing basic data on the surface distribution of radioactivity. Normally, such surveys are made with car-mounted scintillation counters of the continuously recording type, but occasionally, light portable instruments are used on foot or horseback. Quantitative differences in radioactivity equivalent to about 0.002%  $U_3O_8$  can be easily determined. Instruments mounted in four-wheel-drive vehicles have been successfully used for cross-country traversing in relatively open terrain.



## SURVEY TECHNIQUES \*

Authorities are agreed that Geiger or scintillation counters are virtually indispensable for prospecting for uranium—although they should not be regarded as rendering ordinary techniques unnecessary—and that few of the occurrences found since about 1946 would have been discovered without use of counters. This is mainly because the uranium minerals in these deposits are usually dispersed rather than massive and are therefore difficult to see; and because the secondary minerals, which aid in visual detection when exposed, are commonly washed or dissolved from the actual exposed rock surface and are more likely to be found after breaking into the rock where a counter has registered a reaction.

For ordinary work it is generally considered that the smaller Geiger counters equipped only with earphones are satisfactory. They have the advantages of being smaller, lighter, and cheaper than the more elaborate models. In general, the cheapest ones seem to get out of order too frequently; those costing from about \$100 to \$150 are fairly satisfactory, although it is advisable to have a spare in reserve. Misleading results are commonly obtained as a result of the "mass effect" of a body of slightly radioactive rock. Prospectors are advised to consider counts obtained from outcrops, drill core, and other fairly large amounts of rock only as an indication that it is worthwhile to take a few hand specimens or chip samples. These are then carried to a place where the background is normal, and held individually against the counter. If each fails to cause a count of two or three times background, the samples may be discarded and the occurrence ignored; but if the count is raised to this amount or more, the sample concerned, and perhaps additional ones found by further search, should be sent for assaying.

Geiger or scintillation counters equipped with meters are desirable for prospecting or studies in connection with low-grade deposits and rocks, for examinations of prospects by engineers or geologists, and for making special radioactivity surveys. The latter, which are usually plotted as contoured radioactivity plans, have proved very useful for detailed prospecting after a small favorable area has been outlined. Readings are taken along lines to form a grid with intervals of 100 to 10 feet, depending on the circumstances, and the counter is moved slowly from station to station in case a marked rise in count is obtained between the regular stations. For work of this kind scintillation counters seem preferable in most respects except price, but satisfactory results are obtained under most conditions by using good meter-equipped Geiger counters, which cost about half as much as scintillation counters.

\* From Geneva Conference Paper 1, "Uranium Prospecting in Canada—Ground and Aerial Surveys" by A. H. Lang, Geological Survey of Canada.



Another method—which may be called the “routine method”—is simply to test with a counter all outcrops, pits, dumps, etc., in an area, or specimens in a collection. Important discoveries have resulted from the detection of radioactivity in a specimen that did not appear to contain uranium and that had been in a collection for years. Minor discoveries have been made by testing old prospects opened up for gold or other metals.

In the examination of discoveries, counters are very useful in several ways, but they do not eliminate the need for sampling. They help in deciding whether it is necessary to take many samples. Furthermore, testing samples with the counter may indicate that they are so low-grade that they can be discarded; and for some fairly regular deposits, fewer samples need be taken than for, say, a gold deposit, if counter readings are substituted for a proportion of the samples that would normally be taken. It seems that at best, counter readings can be considered only semiquantitative, because the distribution of minerals in a deposit is not regular. Detailed grid surveys with a counter are often useful in judging discoveries and in planning their exploration, but such surveys must be made before any blasting is done, otherwise the area is likely to be contaminated by radioactive debris.

The method of exploration is determined by the characteristics of each deposit. In general, the tendency in Canada is now to do a minimum of surface stripping and trenching and to rely largely on diamond drilling, which is usually followed by underground exploration from an adit or shaft if drilling gives favorable results. Some deposits, however, are sufficiently regular in shape and mineral content to permit estimation of tonnage and tenor from drill core alone. It is customary to test core with a hand counter, then to split the sections that show appreciable radioactivity, and to send one half for assay. It seems that only experience with a particular counter and type of deposit will indicate the reading at which core should be considered worth assaying; until this is learned, it is best to err on the side of obtaining too many rather than too few assays.

The custom is to have most assaying done radiometrically, because this can be done relatively cheaply, and to have a certain proportion checked chemically or fluorimetrically. The recently developed “equilibrium counter” \* has proved useful for making radiometric assays for uranium irrespective of disequilibrium and thorium content.

A few prospectors, engineers, and geologists working in remote places make approximate radiometric assays with a field counter, after the method described by Senftle,† and make fluorescent bead tests to distinguish between uranium and thorium.

\* Not widely used as of this writing. [Ed.]

† F. E. Senftle, 1949: *Determination of Uranium in Ores by Field Analysis*. Memorandum Series No. 96, Dept. of Mines and Technical Surveys, Ottawa, Canada.



If an unusually large amount of core is to be tested for radioactivity, an apparatus may be arranged whereby a box of core is pushed along a bench, under a Geiger tube set transversely to the rows of core and slightly above it. The tube is shielded at the sides and top with lead blocks and is wired to a counter having both a meter and an earphone that is amplified by a loud speaker. Trial and error will permit adjustment to what is considered a significant reaction. When this is obtained, the individual rows of core in the box are tested, and the meter readings are logged.

Portable counters are useful for examining underground workings, in the same way as in examining surface showings, and they are also useful in a semiquantitative way for deciding whether mined rock should be classed as ore or waste. When using a counter underground the operator usually has to accustom himself to a higher background than that prevailing at the surface. If much use is to be made of a counter underground, it is preferable to have a separate one for that purpose, because dust and mine water are likely to contaminate it, thus causing a higher background than is desirable for surface use. Special counters equipped with end window tubes have been built for underground use, but they are not widely used.

\* In large copper, gold, and other mines the presence and approximate distribution of uranium mineralization underground can be detected by examining the various upcast ventilation fans for radioactivity with a field counter. Any high radioactivity present is due mainly to the daughter products of radon, which are deposited from the upcast air, together with mineral dust on the grille protecting the rotating fan blades.

\* From Geneva Conference Paper 764, "Methods of Prospecting for Uranium and Thorium" by C. F. Davidson and S. H. U. Bowie, Geological Survey of Great Britain.



# *Chapter 11*

---

## AERIAL RADIOMETRIC TECHNIQUES

---

### BASIC CONSIDERATIONS \*

Instruments used in air-borne surveying must be sufficiently sensitive to measure unambiguously a small change in radioactivity at an air distance governed by aircraft safety. Large-volume thallium-activated sodium iodide crystals or plastic scintillators are almost universally used as the radiation detector. High-efficiency Geiger-Müller counter tubes having a multiple-plate cathode structure are occasionally used as the detector. Most instruments are counting-rate meters of the continuously recording type and are specifically designed for installation in aircraft. In addition to the radiation detection instruments, equipment in multiengine aircraft usually includes instruments for accurately locating the position of the aircraft in respect to ground.

Helicopters, light single-engine aircraft, and long-range multiengine aircraft have been used for air-borne surveys, dependent on the objectives of the particular survey and on the location of the area in respect to the operating base. In regard to objectives, air-borne techniques are analogous to surface techniques in that local, detailed, and regional surveys can be distinguished. In selecting an aircraft it is essential that the aircraft have sufficient range to spend a significant proportion of the total flying time over the area to be surveyed.

The spacing of flight lines for air-borne surveys is governed largely by the problem involved. The width of the zone from which anomalous radioactivity can be detected is approximately twice the distance of the aircraft above the ground. As a detector at the 500-foot flight level covers a swath approximately 1000 feet wide, a flight-line spacing of one mile results in about 20% of the area being actually surveyed. For detailed surveys the flight level and spacing of flight lines are decreased, but for regional surveys the spacing may be increased to give only partial coverage.

\* From Geneva Conference Paper 511, "Instruments and Techniques for Measuring Radioactivity in the Field" by F. W. Stead, U.S. Geological Survey. Selected references are listed alphabetically at the end of the chapter.



The absorption and scattering of gamma radiation at considerable air distances from a natural radioactive source place an effective upper limit on the flight level of air-borne surveys. The initial radiation intensity from a natural point source of radiation is decreased to about  $\frac{1}{1000}$  at an air distance of 500 feet. Few air-borne surveys are made at air distances greater than 500–600 feet, and most surveys are made at air distances of less than 200 feet. Although light, portable instruments can be used effectively in aircraft flying very close to the ground, the rapid attenuation of gamma radiation with distance from the source requires relatively large instruments of the highest possible sensitivity to obtain satisfactory measurements at higher flight levels.

Quantitative interpretation of air-borne survey data is not necessary for most applications. The sought-for target is a radioactivity anomaly, a sharp local increase in radiation intensity. The results of the majority of air-borne radioactivity surveys are reported without semiquantitative or quantitative distinction among the anomalies. Anomalies simply indicate localities of more-than-average radioactivity where there is a greater probability of the occurrence of uranium and thorium deposits.

The possibility of quantitative interpretation of air-borne survey data has been extensively investigated. Based on experimental measurements at various air distances over known broad sources of radiation and over a simulated outcrop of uranium ore, considerable progress has been made in establishing the interpretation of air-borne radioactivity measurements in terms of the equivalent uranium content of the source. The radiation from broad sources of semi-infinite extent, such as a sedimentary horizon, can be satisfactorily estimated to within a few thousandths of a per cent equivalent uranium; for example, air-borne radioactivity measurements at 500 feet above a shale were interpreted at  $1.7 \times 10^{-3}$  per cent equivalent uranium, and laboratory analyses of representative shale samples showed 1 to  $2 \times 10^{-3}$  per cent equivalent uranium.

The radiation from a naturally occurring "point" source, such as uranium ore exposed over a few thousand square feet, has proved difficult to interpret in terms of the probable equivalent uranium content and the area of exposure. No simple means of distinguishing between a small outcrop of high-grade ore and a large area of slightly abnormal radioactivity has as yet been developed. It is probable that current research on the scattering and absorption of gamma radiation in two media, air and the source proper, will improve the interpretation of air-borne survey data.

#### TYPES OF AIR-BORNE SURVEYS

**Local surveys.** Local air-borne surveys are usually made with light single-engine aircraft flown at 100 feet or less above the ground. A scintillation count-



ing-rate meter of the nonrecording type is frequently adequate. An observer, preferably a geologist familiar with the area, records on a suitable base map the localities where a sharp increase in radioactivity is shown on the meter. This application is qualitative and is essentially an extension of prospecting on foot. Although random surveying of outcrops may be done, the usual method is to follow favorable outcrops whether on a cliff face—rim flying—or on a horizontal surface. The most successful application of low-level air-borne surveying has been in locating additional deposits in and adjacent to uranium mining districts.

**Detailed surveys.** Detailed air-borne surveys can be made with any type of aircraft and are applicable to areas ranging from a few square miles to a few hundred square miles. The prime requirement is that the radioactivity measurements must be accurately located with respect to the ground, either by visual recognition, by photographic methods, or by electronic navigation methods (radar, shoran, decca, etc.). The radiation detection instruments are usually of the continuously recording type, and the radioactivity measurements have been reported as spot anomalies, radioactivity profiles, or isoradioactivity contour maps.

Detailed surveys are best applied to areas that might contain extensions of known uranium deposits or that contain rock types and structures known to be favorable for the occurrence of uranium. Surveys flown on a predetermined grid pattern have been highly successful in many parts of the western United States, and the results of many such surveys have been released as maps showing the spot location of radioactivity anomalies.

The results of a few surveys have been released as maps showing relatively large areas of anomalous radioactivity. Isoradioactivity contour maps have been compiled from detailed air-borne surveys made by helicopter.

Moxham, Walker, and Baumgardner investigated the relationship between the anomalously high radioactivity recorded during a detailed air-borne survey and the surface distribution of radioactive materials. The data both from a detailed ground radioactivity survey and from the air-borne survey made at the 500-foot flight level are presented as isoradioactivity contour maps. Comparison of the two contour maps indicates that the air-borne isoradioactivity contours conform closely with the ground contours, and that only minor detail is lost at the 500-foot level. Also, comparison between the two isoradioactivity contour maps and the geologic map indicates that some crystalline rocks of various ages and types can be distinguished by their characteristic radioactivity. The radioactivity measurements made at the 500-foot level could discriminate changes equivalent to 0.001% uranium and were made far more rapidly and cheaply than were the ground measurements.

**Regional surveys.** Regional air-borne surveys covering from hundreds to thousands of square miles are usually made with multiengine aircraft flying at



a nominal 500-foot altitude and at a flight-line spacing of  $\frac{1}{4}$  mile. Highly sensitive scintillation counting equipment is normally used. Associated instruments are carried for determining continuously the position of the radioactivity measurement in respect to ground. Frequently, aeromagnetic measurements are made in conjunction with the radioactivity measurements, thus providing valuable data at little increase in cost.

Regional air-borne surveys differ from detailed surveys partly in the scale of operation and partly in that the objective is to find large and new areas in which radioactive raw materials might occur. Areas for survey are selected largely on geologic inferences as to where uranium and thorium are most likely to occur, rather than being selected on direct evidence such as known favorable rock types and structures or uranium deposits in the area. Regional surveys have proved quite successful in locating new areas not previously known to contain uranium.

Under favorable conditions, air-borne surveys of large areas offer promise as a rapid and cheap method of reconnaissance geologic mapping. Many rock and residual soil units show a characteristic radioactivity that could be correlated with particular formations by limited ground examination.

Currently, the surface variation in over-all radioactivity between and within rock units is being investigated as a means of delimiting large areas favorable for radioactive ores. Recent data suggest that in metamorphic and igneous terranes the uranium deposits may occur in large but localized areas where the radioactivity of the country rock is significantly different from adjacent areas of similar rock types. The target or favorable areas in crystalline rocks might be measurable in square miles rather than in terms of a local concentration of a few hundreds of square yards as is the case in sedimentary terranes. The possible application of regional air-borne surveys in locating such large targets is highly attractive, particularly as the survey could be made at wide spacing of flight lines and at high flight level, possibly at the 1000-foot level.

#### QUANTITATIVE INTERPRETATION: AIR SCATTERING EFFECTS \*

A knowledge of the air scattering of gamma rays from naturally occurring thick uranium sources is necessary to interpret radioactivity measurements made at considerable air distances from sources. As currently applied, air-borne radioactivity surveying is essentially a qualitative technique, that is, anomalously high radioactivity relative to the immediate surroundings is used to guide ground investigations to localities where radioactive deposits of economic importance might occur. The interpretation of measurements should be placed on a quantitative basis if the technique of air-borne radioactivity surveying is to be further developed as a geophysical tool. For satisfactory

\* From Geneva Conference Paper 518, "Air Scattering of Gamma Rays from Thick Uranium Sources" by A. Y. Sakakura, U.S. Geological Survey.



interpretation, the various observable quantities recorded by a counting-rate meter, such as the peak intensity (counts per second), total number of counts (the area under the curve), and the shape of the curve must be correlated with the principal characteristics of a natural source, namely, the grade in terms of the equivalent uranium oxide content and the configuration in terms of the surface dimensions.

As the fundamental properties of gamma radiation are well known for the energy range from natural sources, the ideal method of interpretation would be based on the theoretical computation of the radiation intensity emanating from sources of various configurations. The advantage of the computational approach is that the results do not have to be resolved in terms of the response characteristics of a particular detector. Where the radiation source is distributed in one medium, rocks and soils, and is measured at considerable distances from the source in another medium, air, the intensity of scattered radiation predominates over that of primary radiation; thus a numerical solution of the Boltzmann equation for the gamma-ray transport in two media is necessary. The solution of this equation is, in general, a function of three space variables (coordinates of the point at which the radiation intensity is computed), two angular variables (scattering), and an energy variable for any given source configuration. Once such a solution is obtained, the response of any detector, its spectral and angular characteristics being known, could be computed.

Unfortunately, no satisfactory general solutions to two media problems have been published, although the U.S. Geological Survey with the cooperation of the Computing Facility of the U.S. Atomic Energy Commission at New York University is now engaged in solving the two-media problem with plane symmetry. However, analytical approximations and a vast quantity of numerical solutions to one-media problems in various geometries exist, from which one can predict trends of solutions in two media. Moreover, for high-energy radiation traveling in a forward direction, the presence of the boundary is immaterial. The general procedure in solving the Boltzmann equation was developed by Spencer and Fano at the National Bureau of Standards. A further source of difficulty in detail, if not in principle, in solving the Boltzmann equation is that the uranium source spectrum is very complex, necessitating the solution of many problems with different primary source energies and the superposition of these individual solutions. An alternative approach to the approximate solution of the two-media Boltzmann equation consists of using the existing solutions computed for simple geometries and the knowledge of the gamma-ray spectrum of uranium. Then these solutions are combined according to educated guesses as to what the two-media solutions should be from a previous knowledge of simple geometric solutions and analytical behavior of the solutions.

However, the simplest approach is a semiempirical one, wherein an experimental or assumed form of radiation-intensity law for an elementary source



is integrated over a suitable geometric configuration to obtain the intensities from various sources. Peirson and Franklin made such an integration, assuming an inverse-square exponential law, which not only neglects the effect of scattering but also the many lines of the uranium spectrum. Carmichael and others used the inverse-square law but considered air scattering by experimentally determining the "effective absorption coefficient" from measurements of the radiation from radium sources. Cook assumed an "effective" energy and used effective computed cross section and the inverse-square law. However, there is no a priori reason why an effective cross section measured or calculated in one source-to-medium orientation should be applicable to others.

To avoid this conceptual difficulty, measurements were made on infinitely thick, "point," and broad sources. In this way the integration in depth has already been performed. An effective point source can be obtained when the areal extent of the source is small compared to the air distances at which measurements are made. Others sources are synthesized from the point source data through integration over a surface.

Although a semiempirical approach is adopted it is convenient to retain the structure of the theory, especially for extrapolating the data to areas not covered by the experimental measurements. Thus the intensity is represented by the product of the unscattered contribution of the most penetrating component and a build-up factor for the scattered radiation, which for moderate penetration is a polynomial in the distance variable.

**Gamma intensity from various idealized sources.** The two fundamental sources are:

1. Elementary point source, the line depicted in Figure 11.1.
2. Infinite broad source, the region  $x = < 0$  filled uniformly with radioactive material, shown in Figure 11.2. Obviously, in this case, the source is an infinite superposition of the elementary sources. Thus, a functional form

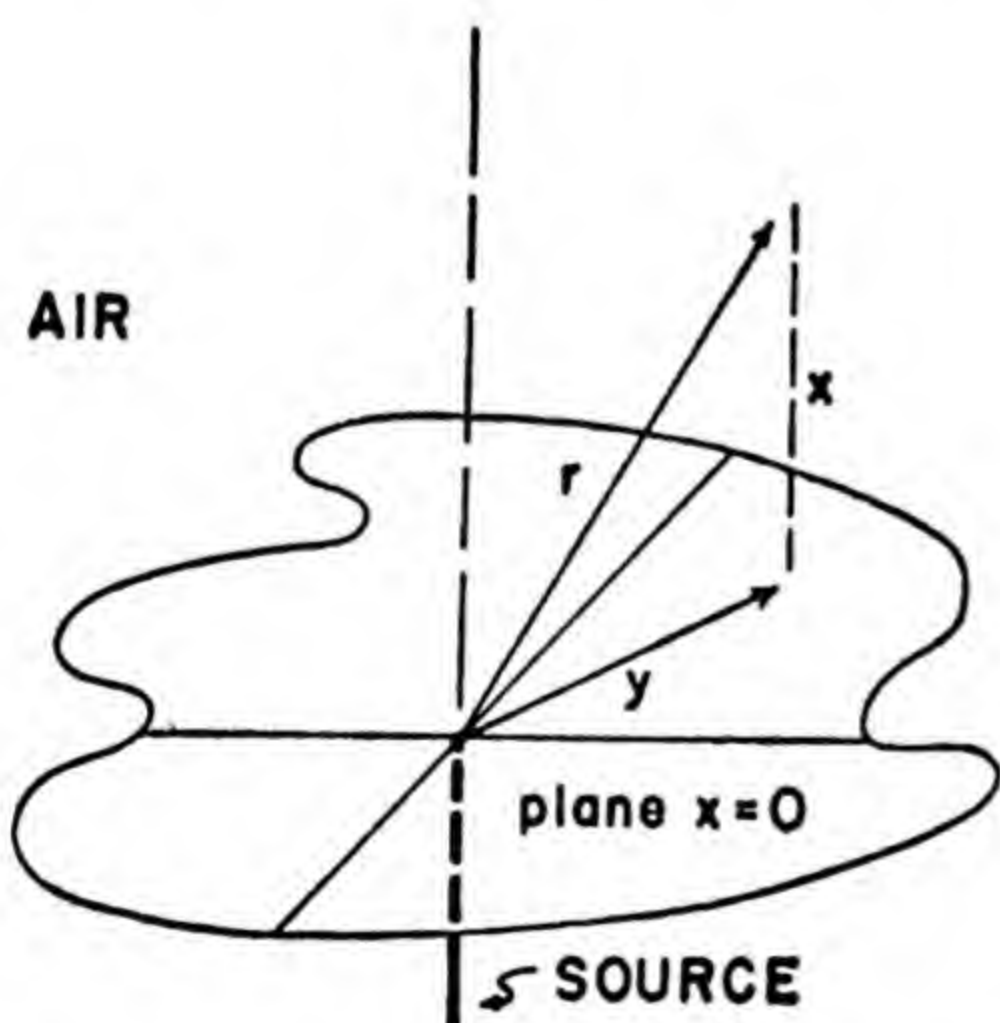


FIG. 11.1. Elementary point-source geometry.

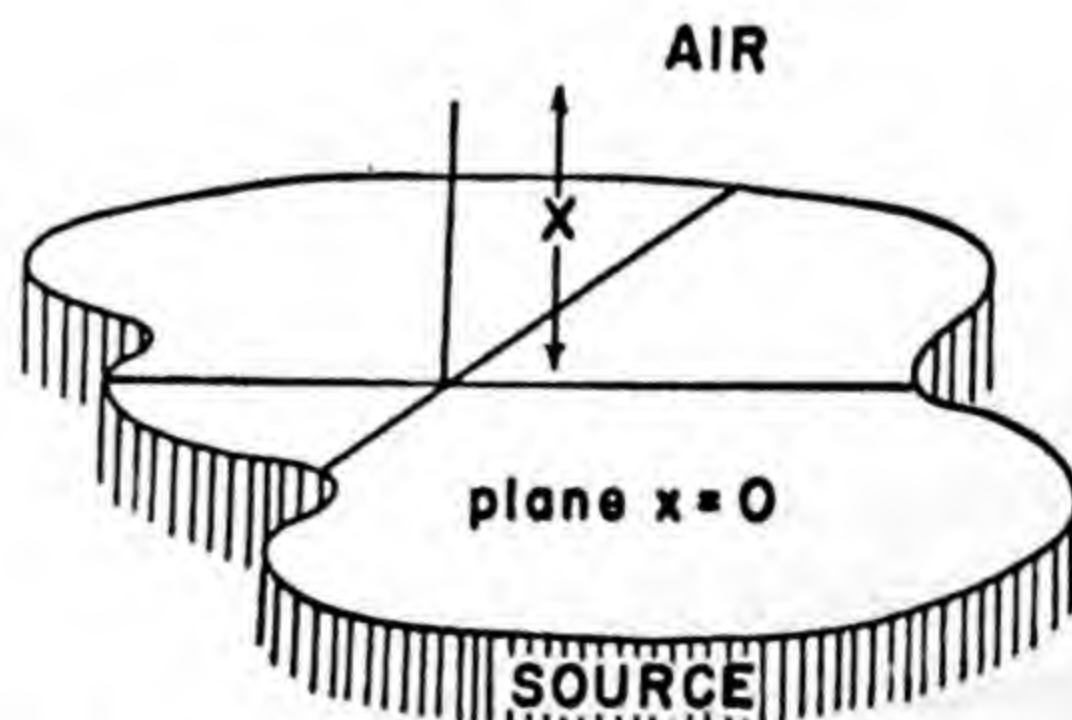


FIG. 11.2. Infinite broad-source geometry.



dictated by theory is chosen for the elementary source, and the constants are selected so that the expression fits the elementary-source experimental data, and the result of integrating this expression over an infinite surface fits the infinite-source experimental data.

The intermediate source types are:

1. Line source, an infinitely long source of breadth,  $a$  much less than the diameter of the elementary point source. The intensity  $I_l(x, y, a)$  is a function of altitude  $x$ , and  $y$ , the distance from the point of observation to the axis of the source, projected onto the plane of the source.

2. Slab source, a source intermediate between the line source and the infinite broad source. Its length is assumed to be infinite. The intensity  $I_s(x, y, a)$  is a function of altitude  $x$ , the ground projection  $y$  of the distance from the observation point to the center axis of the source, and breadth  $a$ .

3. Finite source, a circular source of diameter greater than an elementary source and less than an infinite source. The intensity  $I_f(x, y, a)$  is a function of the altitude  $x$ , the ground projection  $y$  of the distance between the detector and the center of the source, and the diameter  $a$ .

All the solutions can be expressed in closed form except for the last source. Numerical computations show that for a detector at an altitude of 500 feet, the following conclusions can be drawn:

1. Finite sources of diameter greater than 1700 feet and slab sources greater than 1200 feet in breadth are infinite sources.

2. Finite sources less than 550 feet in diameter are point sources.

3. Slab sources less than 800 feet in breadth are line sources.

4. Line and slab sources must be 1700 feet in length to be considered infinitely long.

**Area under counting-ratemeter curve.** Knowing the response of the instrument and the velocity of the detector, the areas under the curves can be computed for various source configurations and grade. These areas are:

1. ELEMENTARY POINT SOURCE. The area  $H_p(v, x, \xi, a)$  is a function of the altitude  $x$ , ground projection  $\xi$  of the distance of closest approach between the detector and the center of the source, velocity  $v$  of the detector, and diameter  $a$ .

2. FINITE SOURCE. The area  $H_f(v, x, \xi, a)$  is a function of the same variables as above.

3. LINE SOURCE. The area  $H_l(v, x, \theta, a)$  is a function of altitude  $x$ , velocity  $v$ , breadth  $a$ , and  $\theta$ , the acute angle between the normal to the axis of the source and the ground projection of the flight line.

4. SLAB SOURCE. The area  $H_s(v, x, \theta, a)$  is a function of the same variables as above.

Cases 2 and 4 have been evaluated numerically for a 500-foot altitude. The others can be expressed in closed form.



**Interpretation of anomalies.** The unknown factors that enter into the interpretation of an anomaly are the source position relative to the detector, its size, and its grade. As the usual practice is to make continuously recorded measurements along equally spaced, constant-altitude flight lines, the location of the anomaly along the direction of flight can be determined approximately. The source would be located along a line which passes through the peak position of the anomaly and which is at right angles to the flight path. Assuming the source symmetries described above, the shape of the source is reduced to one variable (breadth of line or slab source or radius of a point or finite source). Thus there are three unknowns to relate to the observable quantities. The most obvious one is the peak intensity reading. Another is the area under the curve. The third is the shape of the anomaly, such as its slope and its half-maximum value. However, examination of the computed values shows that the slope varies slightly as the grade-area of the source is increased. Moreover, if one were not flying directly over the source, the anomaly would broaden considerably. An objection to analysis of shape is the fact that the shape would be most susceptible to the variation in position of an air-borne detector. Thus on a given line of observation, one has two observables and three unknowns on one line, or four observables and three unknowns on two lines. Consequently there are two categories of anomalies: those that are visible on two or more adjacent lines, and those that are visible only on one. On the latter the information is necessarily incomplete.

Computations reveal that at a nominal 500-foot flight altitude and at a line spacing of  $\frac{1}{4}$  mile, an ore-grade body (0.1%  $U_3O_8$ ) with a minimum radius of 60 feet located midway between the two flight lines is detectable. As any finite source under 275 feet in radius can be considered a point source which really has only two observables, the grade-area and the distance from the detector, any ore-grade body visible on only one flight line is completely specified. In this case the grade area can be mathematically expressed in terms of the two observables, that is, the peak intensity and the area under the curve.

If the anomaly is visible on two adjacent lines, there are four observables on hand:  $H_f(x, \xi)$ ,  $I_f(x, \xi)$ ,  $H_f(x, d - \xi)$  and  $I_f(x, d - \xi)$ , where  $d$  is the spacing of the lines. As the grade of deposits ranges widely, one requires grade-independent quantities. Two of these are:

$$\frac{H_f(x, d - \xi)}{I_f(x, d - \xi)} = R_f(x, d - \xi)$$

$$\frac{H_f(x, \xi)}{I_f(x, \xi)} = R_f(x, \xi)$$

If one were to use the computed quantities and plot  $R_f(x, d - \xi)$  vs.  $R_f(x, \xi)$ , a series of curves for different values of  $a$  would be obtained. With the use



of observed quantities,  $a$  can be determined from this plot. Moreover, it is found that when the point-source formulas relating grade area to  $I_p$  and  $H_p$  are applied to finite source values at  $d - \xi$  and  $\xi$  and the resulting grade-area values are then averaged, the averages are constant for all values of  $\xi$  at fixed  $a$ . These averages can be corrected with true grade areas by multiplication with a conversion factor. The procedure is then:

1. Compute  $H(x, \xi)/I(x, \xi)$  and  $H(x, d - \xi)/I(x, d - \xi)$  to determine  $a$  from a precalculated plot of  $R_f(x, d - \xi)$  vs.  $R_f(x, \xi)$ .
2. Compute grade area at  $\xi$  and  $d - \xi$  using the point-source formula, and take the average of the two values.
3. Multiply the average by a precalculated factor for a given  $a$ .

This procedure gives the grade area of the finite source, and from the grade area and  $a$ , the grade.

The preceding discussion refers only to finite sources. Line and slab sources, by definition, will yield the same peak reading and area on two adjacent lines. The ratio  $H_s(x, \theta) \cos \theta / I_s(x, \theta) = H_s(x, 0) / I_s(x, 0)$  yields the value of  $a$  for line and slab sources. The factor  $\theta$  is determined from the relative position of the anomaly on two adjacent flight lines. Then the application of the expression for the slab-source area under the curve yields the grade-breadth, and consequently, the grade.

If the anomalies show decided flattening at the peak, application of the expression for an infinite source evidently will yield the grade. Moreover the breadth at one-half peak intensity denotes the breadth of the source. This aspect of the calculations has been amply confirmed by ground investigations.

In the case of a compound anomaly reflecting two or more separate point sources, the separation into individual sources and the determination of the respective  $H'_s$  and  $I'_s$  presents some difficulties.

**Summary.** Certain general concepts underlying the semiempirical approach to the interpretation of air-borne radioactivity measurements warrant attention, although the particular method presented here is not entirely satisfactory for all aspects of interpretation. These concepts are:

1. Use of an elementary point source of infinite thickness. This eliminates the necessity of assumptions that scattering and absorption of gamma radiation are not influenced by the presence of a boundary between media and that the scattering effect of a medium is dependent only on the electronic density.
2. Use of point and infinite broad-source behavior to fix the analytical form of the elementary function.
3. The investigation, numerically and analytically, of relationships among observables and source characteristics.

The combination of observables selected for analysis is not uniquely valid



to an adequate interpretation. Other combinations yielding an equal or greater amount of information would also be valid. For example, after identifying the source type, the grade could be computed as though the source were either directly under the detector or at the point midway between two adjacent flight lines, thus obtaining values for the two extremes of grade.

It must be stressed that there are many approaches to this problem. The interpretation of anomalies presented here has been sufficiently confirmed by ground investigation and sampling of the natural sources to make it seem that this method as now developed is reasonably useful.

#### AERIAL RADIOMETRIC PROSPECTING IN THE U.S.S.R. \*

Aviation is extensively employed in prospecting for deposits of uranium and thorium in the immense territory of the Soviet Union. Several deposits of industrial significance were discovered with its help. The search for radioactive ores by aviation is conducted under the U.S.S.R. Ministry for Geology and Preservation of Mineral Wealth, on a single state plan.

The purpose of aeroradiometric prospecting is to fix with geophysical instruments from the air the radioactivity of mineral rock, and subsequently give geological and geophysical interpretations of the anomalies discovered. Together with the development and improvement of the technique and methods of measuring radioactive geophysical parameters from the air, methods of choosing regions and air routes for survey and of interpreting the results obtained, were also worked out.

A characteristic feature of prospecting for deposits of radioactive ores by aviation is the close, organic correlation between geological and geophysical methods of investigation, which makes it possible for the whole work, from the choosing of the route to the evaluation of the discoveries, to be done by a single air-prospecting party.

**Air-ionization technique.** It is known that the radioactive elements in rock emit penetrating gamma radiation and also discharge into the surrounding atmosphere gaslike emanations, radon and thoron.

In the U.S.S.R. two methods of searching for radioactive ore deposits by air were tested, the air-ionization and the aerogamma methods. The physical premise for the first method was that the radiation of radioactive elements is of essential significance among the ion-forming factors in atmospheric air. Ion formation in the air near the surface of the earth is made up of the following components:

$$\Sigma q = q_{\alpha+\beta} + q_{\gamma} + q_{Rn} + q_{Tn} + q_k + q_a,$$

where

\* From Geneva Conference Paper 625, "Aeroradiometric Prospecting for Uranium and Thorium and the Interpretation of Gamma Anomalies" by V. I. Baranov of the U.S.S.R.



$q_{\alpha+\beta}$  stands for ion formation by  $\alpha$  and  $\beta$  rays of radioelements present in the soil,

$q_{\gamma}$ , for ion formation from absorption of  $\gamma$  radiation emitted by rocks,

$q_{Rn}$  and  $q_{Tn}$ , for ion formation by radon and thoron radiations and their disintegration products present in the air,

$q_k$ , for ion formation by cosmic rays, and

$q_a$ , for the ion formation by radiations of the radioactive sediment on the ground.

Only three ionizing factors,  $q_k$ ,  $q_{\gamma}$ , and  $q_{Rn}$ , have noticeable significance at flying height. Thus, in one of the mountain districts of the Soviet Union the following averages were received, characterizing the relative values of different ionizing factors on the earth's surface and at the height of 150 meters:

TABLE 11.1

Ionizing Components	$q_k$	$q_{\gamma}$	$q_{Rn}$	$q_{Tn}$ and Others
On the earth's surface.....	3.9%	30.8%	42.3%	23%
At 150 m altitude.....	6.5%	24%	69.5%	—

Thus with increasing height,  $q_{Rn}$  comes to the fore among the ionizing factors, and alterations in the air ionization of the air at flight altitude must reflect changes in the concentration of radon. Consequently the air-ionization method is a simple way of determining the air radioactivity.

Taking into consideration the mechanism of diffusive and quasi-diffusive distribution of radon in the air layer near the earth surface and in the atmosphere, it may be calculated that a doubling of the ionization in the lower layers of the atmosphere over a wide area should be observed where there are the following concentrations of uranium in rocks covered with friable deposits \* of diverse thickness:

TABLE 11.2

	Thickness of Cover in Meters				
	2	5	8	10	11.5
Concentration of uranium, in %, causing doubling of atmosphere ionization....	$1.5 \times 10^{-3}$	$1 \times 10^{-2}$	0.1	0.3	1.0

\* Soil, alluvial or glacial cover. [Ed.]



The method of ionization, as distinct from the gamma method, registers not only the total radioactivity of uranium-bearing rocks but their emanating quality as well.

An aspirator condenser, operating by conduction current, serves as the instrument for measuring the ionization of the atmosphere. The conduction current, after proper amplification, is registered automatically on a paper tape.

Tests of the air-ionizing method showed that clearly defined anomalies appear over known ore deposits. But this method gives a great number of false anomalies due to foreign sources of ionization and volume charges in the atmosphere. Further, as a result of the transfer of radon and the products of its disintegration by air streams, determination of the exact relations of the anomalies is complicated. Application of ionization is limited at present; the chief industrial aeroradiometrical method is the gamma method.

**Aerogamma technique.** The object of investigations by the aerogamma method is to measure the gamma radiation of rock in the atmosphere near the surface of the earth. The direct relation between this radiation and the concentration of radioactive elements in the upper layer of rock (to a depth of the first few dozen centimeters) is the premise for the method of prospecting by air. The aerogamma method has been developed to the greatest extent in the supplying of apparatus and in the application of the method. In gamma surveying, both on the earth's surface and underground, a quantitative interpretation of the results is possible, that is, a determination of the content of radioactive elements in rocks directly from the readings of geophysical instruments. In surveying by airplane a difficulty in geophysical interpretation arises due to absorption and scattering of gamma radiation in the air and to various specific interferences.

In actual conditions, with widespread layers of matter and the complex composition of primary gamma photons, it is advisable to make use of the generalized laws of distribution of gamma radiation in evaluating the effect registered by the radiometer from the air.

The most essential concerns the law of the change in intensity and the alteration of the spectral composition of a point source of radiation in an extensive geological medium. In many cases the exponential law proves satisfactory for practical purposes, with a certain effective absorption coefficient depending on the spectral composition of the primary gamma radiation.

In the case of flat extended media, sections of rock formations, the effect on the receiver of the aeroradiometer can be determined according to the basic relation:

$$I = K\epsilon a^{-1} \int_{\Omega} e^{-\frac{\mu F(z_0, \phi\theta)}{\cos \theta}} d\Omega, \quad (1)$$



where

$I$  stands for the intensity of the gamma radiation;

$\epsilon$ , for the weight concentration of the radioactive matter;

$z, \phi, \theta$ , for the cylindrical coordinates, with  $z_0$  = thickness of medium;

$$F(z_0\phi\theta) = \int_0^{z_0} \rho(z, \theta, \phi) dz;$$

$\rho$  stands for the density of the medium;

$\mu$ , for the effective absorption coefficient;

$a = \mu/\rho$ ;

$K$  stands for a constant depending on the character of the primary gamma radiation and the units of measurement;

$d\Omega$ , for element of the solid angle.

The anomaly of the gamma field intensity at the surface of the earth =  $I_0$ ,

$$K\epsilon a^{-1} = \frac{I_0}{2\pi}. \quad (2)$$

For computing the intensity in points of the absorbing medium, air, according to the given distribution of  $I_0$  on the flat border of the section, it is sufficient to know this distribution and the density of the absorbing medium.

An analytical computation of the intensity of gamma radiation at an altitude of airplane flight according to Formula 1 is possible in many cases, but the results are quite inconvenient for practical use. Computing the integral (Formula 1) and neglecting (Formula 2) the gamma field anomaly on the surface of the earth for an arbitrary configuration is convenient and simple with the aid of a nomogram.

In important practical cases of linear anomalies, the relation between the integrated effect on the instrument and the total radioactive matter per unit of length of the anomaly is significant. It can be shown that

$$\int_{-\infty}^{+\infty} I(x) dx = \alpha q \Phi(\mu h) (\sin \phi)^{-1}, \quad (3)$$

where

$I(x)$  represents the intensity of gamma radiation or the impulse counting speed of the Geiger or scintillating radiation receiver at the flying height  $h$ ,

$\Phi(\mu h)$ , the transform function of the value  $I(h)$  for a homogeneous flat extended section,

$\phi$ , the angle between the line of flight of the airplane and the direction of the linear anomaly,

$\alpha$ , a coefficient depending on the choice of measuring units.



The intensity is registered by the aeroradiometer against a background of numerous interferences, such as cosmic radiation, gamma radiation of radioactive emanations in the air, and others. For eliminating these, registering the so-called altitude curve is important.

If  $N = N(h)$  is known, where  $N$  represents the average rate of the receiver's counting of gamma radiations at the height  $h$ , then using known data on the alteration of cosmic radiation in different altitudes,  $n = n(h)$  can be separated out, with  $n$  the counting rate attributable to the gamma radiation of the rock. The presence of serious interferences essentially lowers the accuracy of measuring the rock's gamma radiation itself. Decrease of the inaccuracy of investigations is achieved in different ways. To weaken the influence of cosmic radiation, the coincidence method or an array of Geiger counters is used.\*

In practical aerogamma prospecting, the flight altitude is measured by radioaltimeter with continuous recording of its readings. Corrections due to flight altitude are made in two ways: (a) by calculation (or by nomogram) based on the flight altitude curve, and (b) by automatic correcting during the flight, with the aid of special electronic schemes which take into account both the altitude with respect to the topography, and the height of the airplane above sea level.

Scintillation counters produce, not a single altitude curve, but a series of curves, each of which corresponds to a given discrimination of the scintillation counter. The methods of determining the useful radiation, correcting errors due to the flying altitude, and eliminating interferences are analogous to those described above.

In exploration by air in mountain districts a serious distortion of the gamma field is caused by the relief. It can be shown that minor depressions and elevations to the extent of 10 to 20 meters insignificantly deform the gamma field at a flight altitude of 100 meters. All approximate calculations of the influence of the relief are made with the aid of special nomograms. For altimeters used in modern Soviet airplanes and helicopters, the influence of the relief is determined satisfactorily enough in cases where the relief slopes not more than  $45^\circ$  or  $50^\circ$ . In complex mountain districts, determining the influence of the relief is definitely more difficult. In such cases a special flight method is used, depending on the form of the relief.

An important problem in the search for radioactive ores is the separating of uranium and thorium anomalies directly from the airplane. Work along this line is conducted with Geiger counters of various spectral sensitivity characteristics, or with scintillating counters fulfilling spectrometer duty.

\* For description of coincidence and anticoincidence techniques, see W. C. Elmore and M. Sands, *Electronics: Experimental Techniques*, New York, McGraw-Hill Book Company, Inc., 1949; and Serge A. Korff, *Electron and Nuclear Counters*, 2d ed. New York, D. Van Nostrand Company, Inc., 1955.



The kind of ore content is determined with confidence when the objects under exploration create a sufficiently intense gamma field at the flying altitude.

**Organization of aeroradiometric prospecting.** The choice of districts for prospecting for radioactive ores by airplane is based on structural, metallogenic, and paleogeographical analyses. The work of prospecting is conducted by groups of qualified geologists and geophysicists of the aeroprospecting expedition in three closely bound stages—the search for anomalies, the search for the deposits based on the anomalies, and the evaluation of the deposits.

The aeroexploration expedition is headed by a geologist and is composed of air and land groups. The number of the latter is so determined that all the anomalies disclosed could be evaluated by the group during the trip. The aeroprospecting expedition is equipped with light boring machinery and compressors mounted on automobiles.

Prospecting by air is preceded by scouting surveys by airplane for the purpose of making geologico-geomorphological observations and determining the degree of radioactivity (background) of different rocks characteristic of the district. The main type of prospecting network in level regions consists of a system of parallel routes 250 m apart on an average, 20 to 40 km long, at an altitude of about 50 m. In mountainous regions the form of the relief often complicates the directing of airplanes along routes desirable from the geological standpoint, and in planning the routes the first consideration must be the peculiarities of the relief and the necessity of maintaining the operating flight altitude. Under these conditions helicopters are used. Aerophotography is used for more precise association of the anomalistic sections with the locality.

The tape recordings made during the flight are worked over by the operator, a geophysicist. The final geophysical data are then fixed on the geological map. In cases of significant anomalies, detailed surveys are made from the air, and geophysical and geological and drilling work is started on the ground.

**Interpretation of aerogamma anomalies.** The intensity and size of the anomalistic gamma field registered by the instruments over the radioactive section depends on (a) the surface intensity of the gamma radiation and its distribution over the section, (b) the size and configuration of the sections, and (c) the nature of the radioactive source.

In practice, aeroradiometrical work has shown that a large part of the disclosed anomalies are not connected with deposits of industrial worth. Therefore checking all aerogamma anomalies on the ground causes unproductive expense in labor and material.

The primary problem in interpreting anomalies is rejecting anomalies without promise, where this fact is obvious from both the geophysical and geological data and has no need to be checked or studied on the ground. This problem is solved in accordance with the concrete conditions of each district, on the basis of a series of local indications determined by experiment. For



example, in some cases anomalies caused by varied structure and texture of identical materials, for instance, coarse- and fine-grained granites, and anomalies caused by a diversity in the composition of rocks (a dike of felsite-porphyry in lime) and others may turn out to offer no promise.

It is much easier to point out the indications of anomalies worthy of immediate notice. One of the signs of possible promise of anomalies is their local character on a background of rocks of the same type. All sections with intensified radioactivity may offer possibilities. In level or slightly hilly districts, with a development of thick superficial layers, where outcrops of ore bodies and country rock take up quite a small area, thick deposits of uranium may be found with medium or even lowered radioactivity.

In districts where the country rock is hidden beneath a suite of friable formations, it is worthwhile to note water springs marked by intensified radioactivity. Anomalies are worthwhile which are adapted to zones of tectonic disturbances and to zones of mineralization, especially in rock of the carbonate and basic type, as well as in intrusives and effusives of acid composition. Of special interest are districts with altered coloring of the rock, for instance, districts which bear witness to a process of hydrothermal leaching and districts of iron oxide enrichment with a red and brownish-red coloring.

Anomalies in sustained stratigraphic levels of sedimentary rocks, even in the case of insignificant gamma field intensity, are of interest. In evaluating the importance of anomalies, the possible causation of the intensified radioactivity by other mineral deposits must also be considered. In order to reveal those anomalies for which the lack of prospective worth cannot be established with sufficient accuracy from the geophysical data of the air survey and geological indicators, preliminary check-ups are made on the ground—first of all, geophysically. The final conclusion as to the interpretation of aeroradiometric data can be made after the local indicators have established a connection between individual anomalies and evidence of ores.

**Conclusions.** From experiments in prospecting for uranium and thorium deposits by airplane and the interpretation of their results, we conclude that deposits do not always accompany intensified radioactivity of the rock and that intensified radioactivity of the rock cannot serve as the main criterion in prospecting. Likewise, the evaluation of individual anomalies only by their form and intensity, without comparing all the geophysical and geological data and local evidence, is impossible.

The following methods of work have been evolved in practice for assuring the disclosure of all sections of practical interest, irrespective of the intensity of radiation on the ground.



1. Detailed study of the anomalistic section during the process of aeroradiometrical surveying, with repeated flights, decreased altitude, and *rapprochement* of the routes.
2. Geological surveying and interpretation of anomalistic recordings.
3. Surface checking of anomalies, including radiometric recording and a sufficient amount of mining and mechanical boring.

Since zones of breaks and contacts of different rock and other data show up clearly in aeroradiometrical recordings, geologists extensively utilize these data for greater accuracy in defining the geological structure of the given territory.

#### AERIAL RADIOMETRIC PROSPECTING IN THE UNITED STATES \*

The search for anomalous radioactivity by air-borne equipment is exacting work, replete with hazards for the inexperienced. A complete crew, selected with care for outstanding qualifications, consists of four: geologist-observer, pilot, geologist, and his assistant.

The foremost of these, chief of the air-borne crew, should have, in addition to adequate knowledge of geology, a comprehension of operation of radiation detection equipment, experience in interpretation of aerial photographs, and familiarity with the rudiments of surveying and the principles of sampling. The pilot, on whose quick judgment and instantaneous reaction depend the lives of two men, must hold a commercial pilot license and have not less than 500 hours of flying time in the aircraft of the type, class, and power of that he will be required to operate. Moreover, in order that the unit may be independent of repair depots, he must have a mechanic's aircraft-and-engine rating. The geologist, whose responsibility it is to examine each anomaly discovered, must be as well qualified as the geologist-observer, and since air-borne prospecting may be carried out both near to and distant from civilization, the more qualifications his assistant has, the better.

**Equipment.** Pioneers in the field of air-borne radiometric surveying, Eldorado Mining and Refining, Ltd., of Canada, and the United States Geological Survey (acting for the Atomic Energy Commission) favored in early work the use of multiengine aircraft equipped with scintillation counters coupled to aerial cameras, radar altimeters, and various recording instruments. Applying knowledge gained from this complex equipment, the United States Atomic Energy Commission began the practice of low-level flying with a light two-place fixed-wing plane carrying a scintillation counter. Choice of aircraft

\* From Geneva Conference Paper 510, "Airborne Radiometric Surveying" by T. L. Boyle, U.S. Atomic Energy Commission.



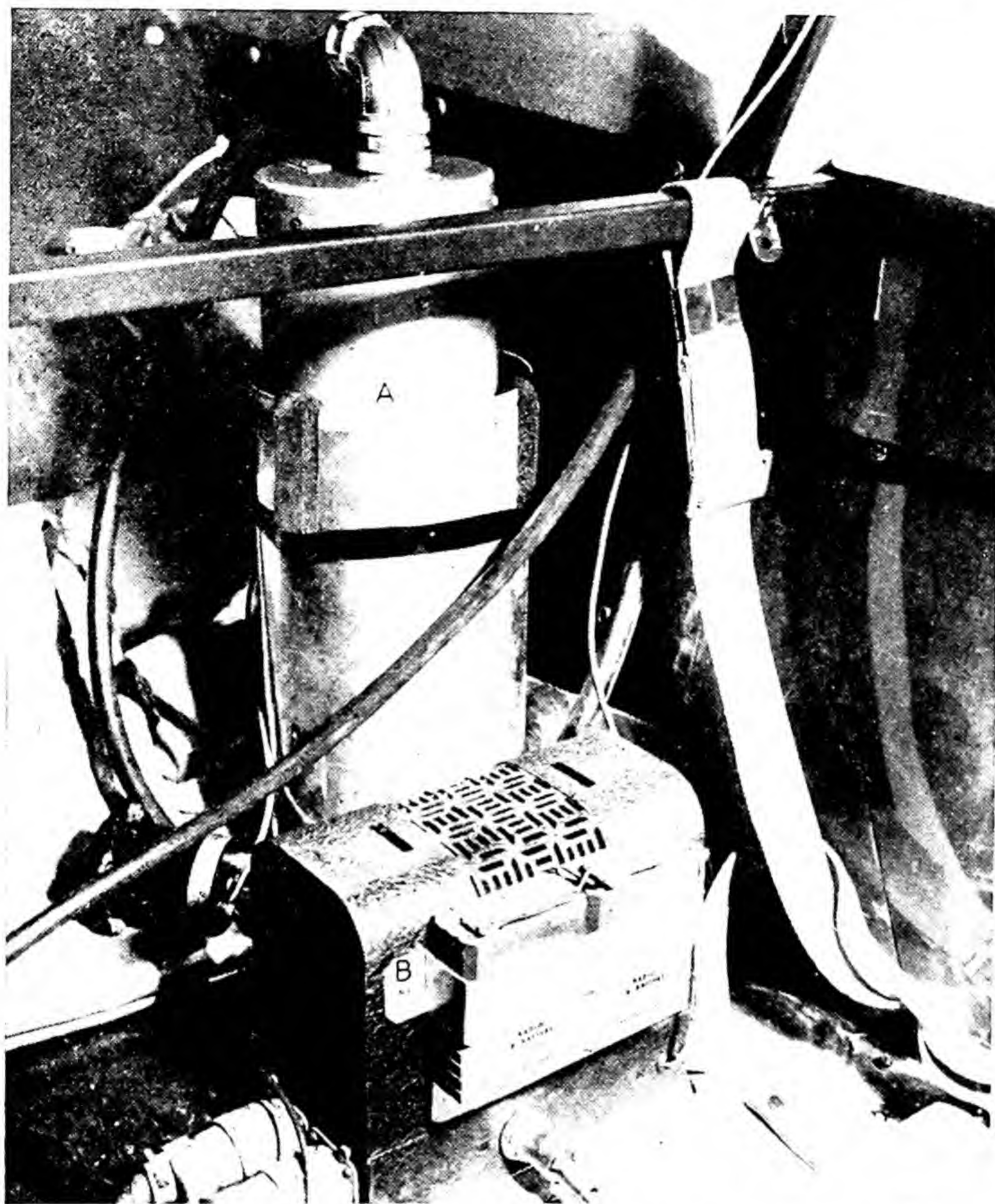


FIG. 11.3. Detector head assembly (A), and power unit (B).

was guided by specifications of exceptional performance and dependability, high maneuverability, low initial and operational cost, ease of maintenance, capability of safe minimum cruising and low landing speeds, and high-wing construction for ground visibility and obstruction clearance on rough landing fields.

A plane meeting these standards is powered with a 135-horsepower engine and has exceptional performance and maneuverability up to 15,000 feet; its purchase price, which includes two wing tanks of capacity allowing five hours of cruising, navigation and landing lights, and two-way radio and shoulder harness for both pilot and geologist-observer, is \$6000. Operational cost—gas, oil, and maintenance—do not exceed, under normal flight conditions, \$7 per hour.



In choice of aircraft for air-borne radiometric survey, helicopters merit consideration. Their high initial cost is a deterrent to their use despite the fact that they may fly and maneuver readily in winds up to 60 miles an hour, and can operate safely at low speeds. Moreover, they traverse readily and at close range, much topography which is inaccessible to fixed-wing craft.

The development in the last few years of scintillation counters, rendered remarkably sensitive by the use of large sodium iodide or plastic phosphor crystals scanned by a photomultiplier tube, has resulted in an excellent instrument for the detection of radioactivity from the air. The detector unit of such an instrument should be mounted in a sponge-rubber-lined aluminum cylinder (Fig. 11.3) to avoid shock and to eliminate vibration as much as possible. Installation in the rear compartment of the aircraft will reduce to a minimum the radiation effect of luminous dials on flying instruments.

The various parts composing this instrument are (1) detector head containing a crystal ( $3\frac{1}{2}$  in. diam. by 2 in. long), photomultiplier tube and electronic circuitry (A in Fig. 11.3), (2) control unit with audio alarm system (Fig. 11.4), (3) power unit (B in Fig. 11.3) consisting of dynamotor (12 volts, 2.5 amperes), stabilizing circuit, and fuses, and (4) aircraft 12-volt battery (mounted in fuselage at rear of cockpit). Use of such an instrument in aircraft flying under ideal conditions at various altitudes at 100 miles an hour (time constant 1.6) has shown that gamma ray emanation from a point source

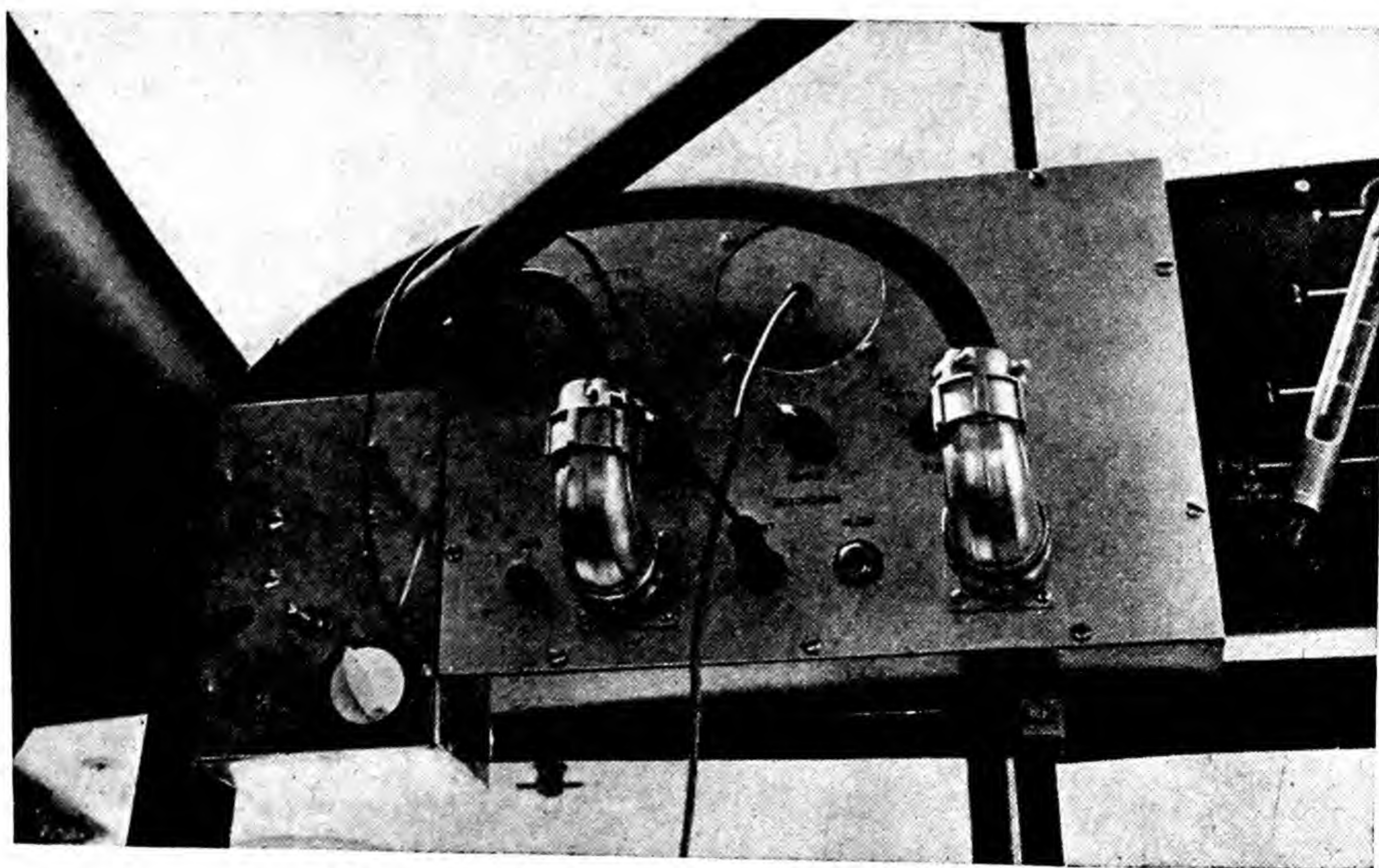


FIG. 11.4. Scintillation counter control unit.



follows the inverse square law which applies in the case of light (Fig. 11.5A).

Figures 11.5B and C incorporate the results obtained in the use of a 3½-inch sodium iodide crystal in flights over a 40-ton point source of 0.3%  $U_3O_8$ . Curves obtained where the plane traversed the source at various altitudes are almost identical to that on Figure 11.5A.

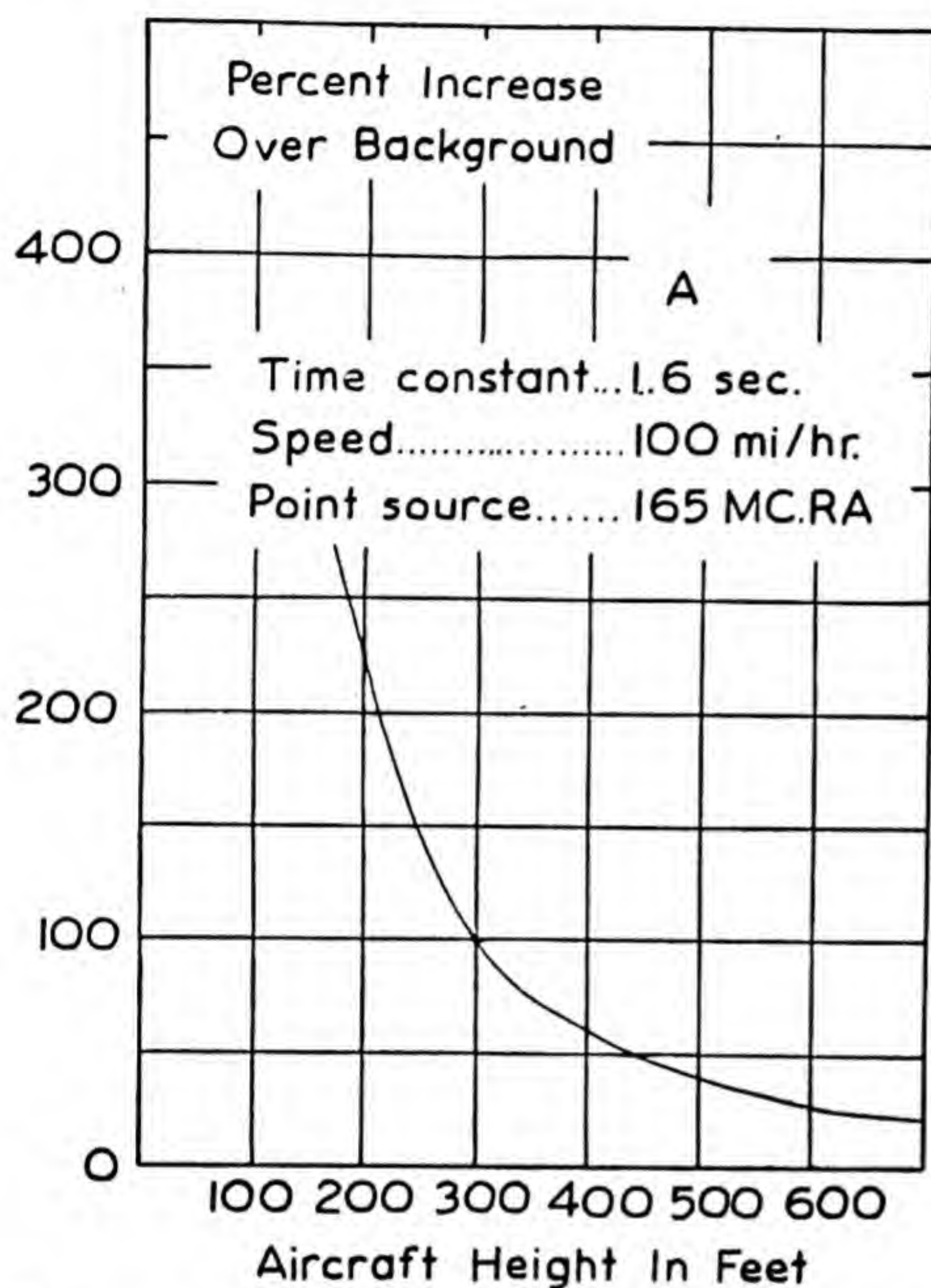


FIG. 11.5A. Aerial scintillometer: The percentage of increase over background vs. aircraft height.

during those early morning hours (dawn to perhaps 9 or 10 A.M.) when the air is calm and at maximum density. During later hours, thermals rising from rough terrain and agitated by winds greater than 15 miles an hour preclude safe flying.

The area to be prospected each morning by low-level flight is first examined at an altitude of 500 feet. Distinctive topographic features marking the boundaries are noted, and a careful search is made for hazards to low-level flight. These vary with the region, but even in remote areas may include telephone and power lines and mine cables extending from valley floor to valley rims. With all hazards carefully noted, the survey may begin with the use of either of two standard procedures which, although as thorough as conditions permit, are judged to give a flight coverage of not more than 50%.

For ground investigation of anomalous radioactivity the geologist and his assistant should be provided with a four-wheel-drive vehicle, complete camping equipment, and portable Geiger and scintillation counters.

**Operational technique.** Whatever the area to be flown over, the operation begins with the recommendation of a geologist familiar with the regional geology and with specific outcrops of the various potential host rocks. Aided by a geologic map of the region and aerial photographs, if available, the geologist-observer familiarizes himself with the topography, ground obstructions dangerous to low-level flight, the outcrop belt of formations to be flown, and such access roads as there may be to the remote corners of the region.

Low-level flight is hazardous, and a reasonable margin of safety demands that it be undertaken only



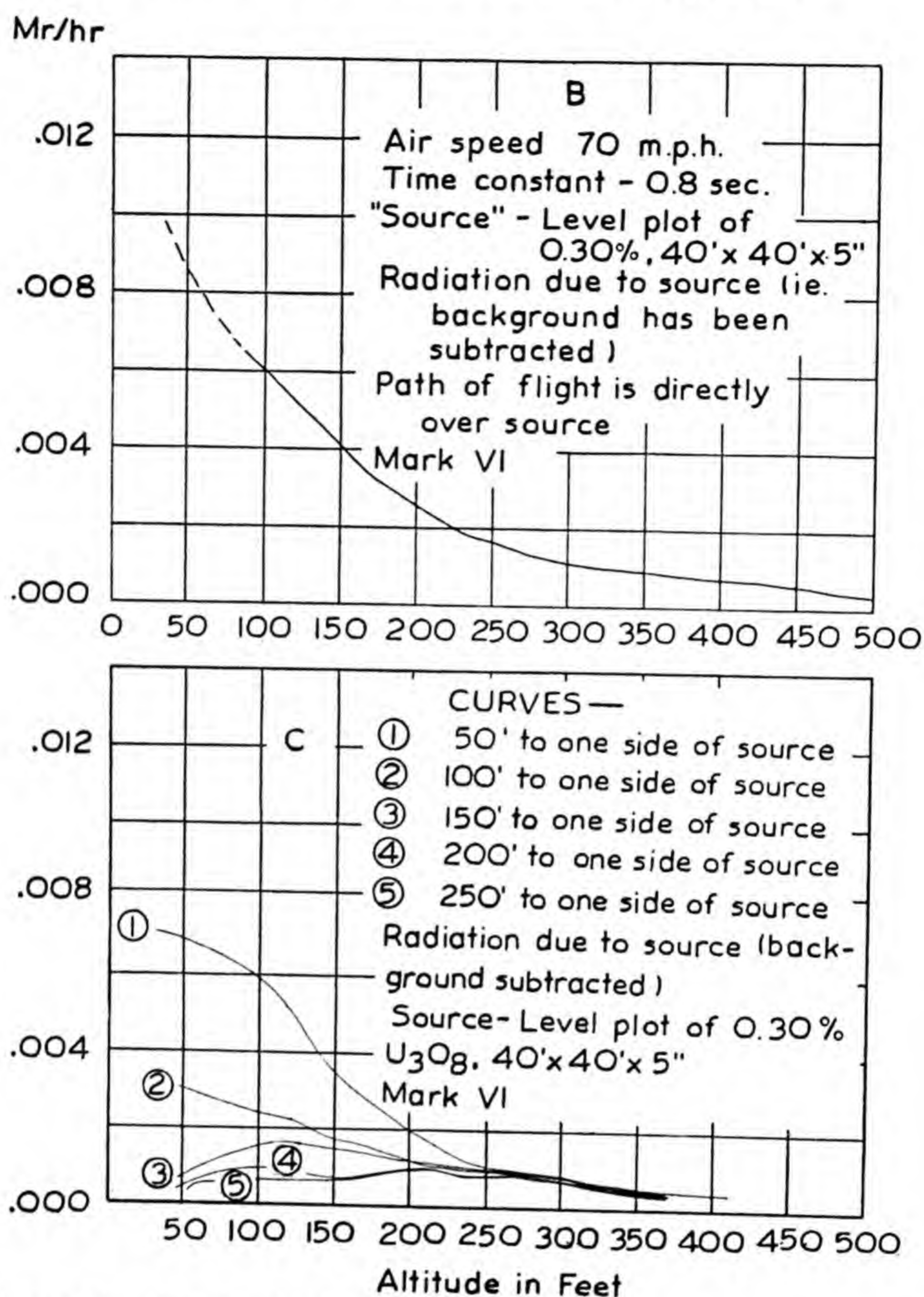


FIG. 11.5B and C. Relation between instrument reading, flight-path and elevation.

In regions of youthful topography—deep narrow canyons separated by wide to narrow divides—formations particularly favorable for the occurrence of uranium may outcrop at any level from valley floor to rim. Among such topographical features it is then necessary to fly the contour of outcrop of the preferred formation at distances 50 feet to 100 feet from it and at a speed of approximately 75 miles per hour.

If the formation under survey is thin, flight along its contour is as continuous as topography will allow; irregular topography may necessitate circling and successive traverses over relatively short outcrop lengths. Should the selected formation be thick—two to three hundred feet—then several passes which will bring the plane within 100 feet of all portions of the outcrop are necessary.



Variations in topography have a great proportional influence on instrument readings when flying close to the ground. This becomes more apparent when flying over rough and deeply dissected terrain. With practice the geologist-observer learns to distinguish between true anomalies and anomalies caused by mass effects or by igneous intrusions.

Where a favorable horizon outcrops in a wide belt of relatively smooth topography it is most economical to fly as closely as is possible on a grid and at altitudes from 100 feet to 200 feet. Such altitudes allow coverage of 100 feet to 200 feet on each side of the aircraft.

Once anomalous radioactivity is discovered from the air, several passes check the intensity, and the spot is plotted on an aerial photograph or geologic map. It is then the responsibility of the geologist to complete a reconnaissance map of the site and to collect representative samples for assay.

**Flight precautions.** In one year of representative operation, approximately 10,000 square miles of grid flying and 10,000 miles of rim flying were completed by seven air crews. In a total of approximately 8400 hours (about 60,000 miles of actual prospecting) of rim and grid flight there were only two accidents, neither of which resulted in serious injury to flight personnel. Neither mishap was the result of personnel incompetence, and in both the aircraft was a total loss. One accident was caused by unforeseeable downdraft, the second a result of collision with a power line spanning a narrow valley, unmarked by right-of-way clearing and rendered invisible by poor postdawn visibility.

There is, of course, no limit to precautions which must be taken in air-borne reconnaissance. Pilots should receive dual flight instruction in the technique of low-level prospecting; they should comprehend the significance of "density altitude." Canyon rims should be flown only on the upwind side of escarpments, and in all cases air conditions must be tested at successively lower altitudes over the area to be flown. Safety harness and "hard hats" should be standard equipment. The more sensitive the detection apparatus, the higher the flight may be made. Canyons in which a 180° turn cannot be executed should not be flown; and in flying vertical canyon walls, the pilot should check his perspective by successively circling and closing his flight path with the cliff face.

**Results.** UTAH. Approximately 620 hours of rim and grid flying over outcrops of Jurassic Morrison and Triassic Chinle and Shinarump outcrops located 95 localities of anomalous radioactivity. The most productive of these was that in the Shinarump conglomerate on the southwest portion of the San Rafael Swell which evolved into the Delta Mine.

ARIZONA. Twenty anomalies were located in the Dripping Springs quartzite (pre-Cambrian) north of Globe as a result of approximately 220 hours of rim flying. It is estimated that half contain material of ore grade.



**SOUTH DAKOTA.** About 455 hours of low-level flying over the outcrop of the Inyan Kara (Cretaceous) in the Black Hills located 36 anomalies from which come about 75% of the production from that region.

In the Slim Buttes region, 10 hours of low-level flight located 10 anomalies in lignites.

**WYOMING.** Air-borne prospecting of Tertiary sediments along various portions of the Big Horn Basin, east flank of the Big Horn Mountains, Hartville Uplift, and Old Woman and Lance Creek anticlines revealed 355 anomalies during 545 hours of flight. About 40 discoveries have produced ore.

**NEW MEXICO.** Flying along the flanks of the Sangre de Cristo and Chuska Mountains and in the Schoole, Magdalena, and Carrizozo districts for 425 hours located 40 anomalies.

#### AERIAL RADIOMETRIC PROSPECTING IN BRAZIL \*

In a country of great size, where air transport has reduced the accessibility problem to such a notable extent, it was only natural that air-borne radiation detection methods should be applied almost from the start of organized explorations. While the air operation cannot be dissociated from ground work, there is no question that the decisive factor in the subsequent discovery of a large number and variety of radioactive mineral occurrences has been the employment of the air-borne scintillation counter and of air methods generally. Air survey, as used in the title to this paper, in fact implies the full integration of air photography, photogrammetry, photointerpretive field and laboratory geology, radiometry, aeromagnetism, and the whole range of operations which are a part of minerals exploration. This presentation, however, emphasizes the aspects of such integrated operations which are most characteristic of the search for uranium and thorium in Brazil and most important to it.

**The air-borne scintillation counter.** An understanding of the organization and techniques of air-borne radiation detection described in this paper demands some familiarity with the primary facility in use. In the simplest terms, this is a specially constructed continuously recording scintillation counter. The instrument incorporates control over sensitivity (the ability to filter out lower-energy radiation), control over the time constant (the ability to vary the period of integration of measurement) and a variable recording scale. The scintillations per minute caused by gamma radiation striking its detecting crystal are counted electronically.

The crystal is mounted in a cylindrical lead shield in such a manner that an approximate 45° downwards cone is "viewed" by the instrument. The

\* From Geneva Conference Paper 132, "Air Survey Applied to the Search for Radioactive Minerals in Brazil" by D. A. MacFadyen and Silvio V. Guedes of Brazil.



viewing axes of a 35-mm positioning camera and of the detector head are parallel. Each exposure of the positioning camera is registered on a moving recording graph, synchronized with intensity measurements. Flying height above ground, measured by a radioaltimeter, is indicated to the pilot and similarly recorded.

The radiometric survey's basic product is therefore a continuous measurement in "profile" form, which may be precisely related to the terrain traversed by plotting of the series of 35-mm positioning photographs in normal vertical air-survey photography. Reduction of air-borne records to map form is a process similar to the compilation of a contour map by a ground surveyor. Points of equal radiation intensity, from a series of parallel traverses, are joined, the resultant "isorads" presenting radiation anomalies in the area sense.

Air-borne radiation detection is usually mapped for convenience in cpm's (recorded counts per minute) rather than in multiples of background or roentgen units, since the latter conventions have limited significance in the practical use of air-survey results.

**Features of air survey which govern planning of operations.** Brazil is a country characterized by deep weathering of surface rocks. This creates problems for the geologist, but its importance to the search for radioactive minerals will be readily seen from the following outline of features which govern the general planning of operations.

From practical experience it has been learned that conducted under proper conditions of weather, with adequate equipment and procedures, air-borne radiation detection is superior to ground radiometry as a means of *locating* significant sources of gamma radiation. The cumulative form of radiation measurement, possible with a moving instrument observing a large surface, results in the ability to detect very low-intensity emanations even at some distance. Quite apart from the obvious advantages of the air method over ground work, having to do with accessibility, speed, volume of information, and cost, the technical superiority of the air-borne method in location is stressed.

In Figure 11.6 is depicted an actual comparison of air-borne and ground scintillometric profiles, with an indication of relief and surface features. It will be seen that the ratio of anomalous signal to background, in the case of the air-borne survey, is four to five times that of the ground survey. It is this much stronger anomalous indication which establishes the superiority of the air method.

The processes of integration which result in higher detectability from the air place a limitation on discrimination, and as a result a series of closely spaced veins or outcrops may form a single unit in a map made from air-borne radio-



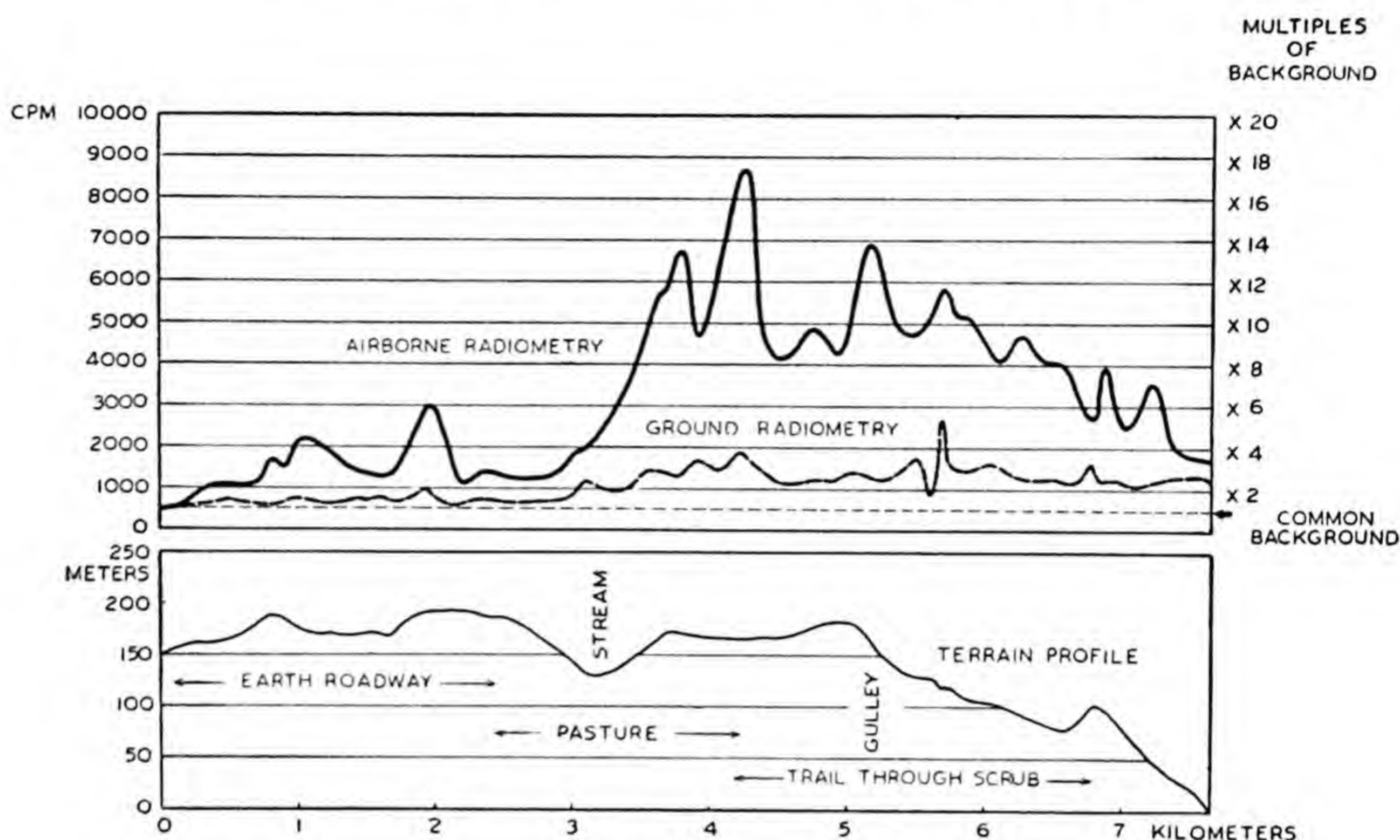


FIG. 11.6. Comparison of air-borne and ground radiometric profiles.

metric profiles. Ground scintillation survey has the advantage of very high discrimination, but demands a dense network of traverses for resolution into plan. It has been found definitely advisable to carry air-borne operations to their limit of discrimination and to supplement them with integrated photo-geological and profile interpretation before commencing the ground radiation detection usually needed even for preliminary surface sampling.

For the high detail needed in the systematic sampling of mineralized areas, and for preparation of drilling plans, ground scintillation surveys are usually required. An interesting feature of the ground scintillation profile shown in Figure 11.6 is the exaggeration of intensity resulting from the solid-angle effect in passing through a narrow gulley.

It is probable that the most effective means of detailed mapping of the radiation pattern within very large mineralized areas is by low, slow-flying helicopter, which compromises between the advantages of areal detection and discrimination-with-proximity.

The weathering of rock and subsequent leaching tend to disseminate radioactive materials over areas much larger than the occurrences themselves, with the result that a *source* of radiation may be indicated from several kilometers away, particularly by the integrated measurements of air-borne survey.

Dependent upon the type of occurrence, reconnaissance surveys, to ensure discovery, may require a highly variable density of flights. The single anomaly zone of Figure 11.7 has a diameter of about 6 kilometers. The unbroken anomaly partly shown in Figure 11.8 has dimensions of roughly  $30 \text{ km} \times 8 \text{ km}$ .



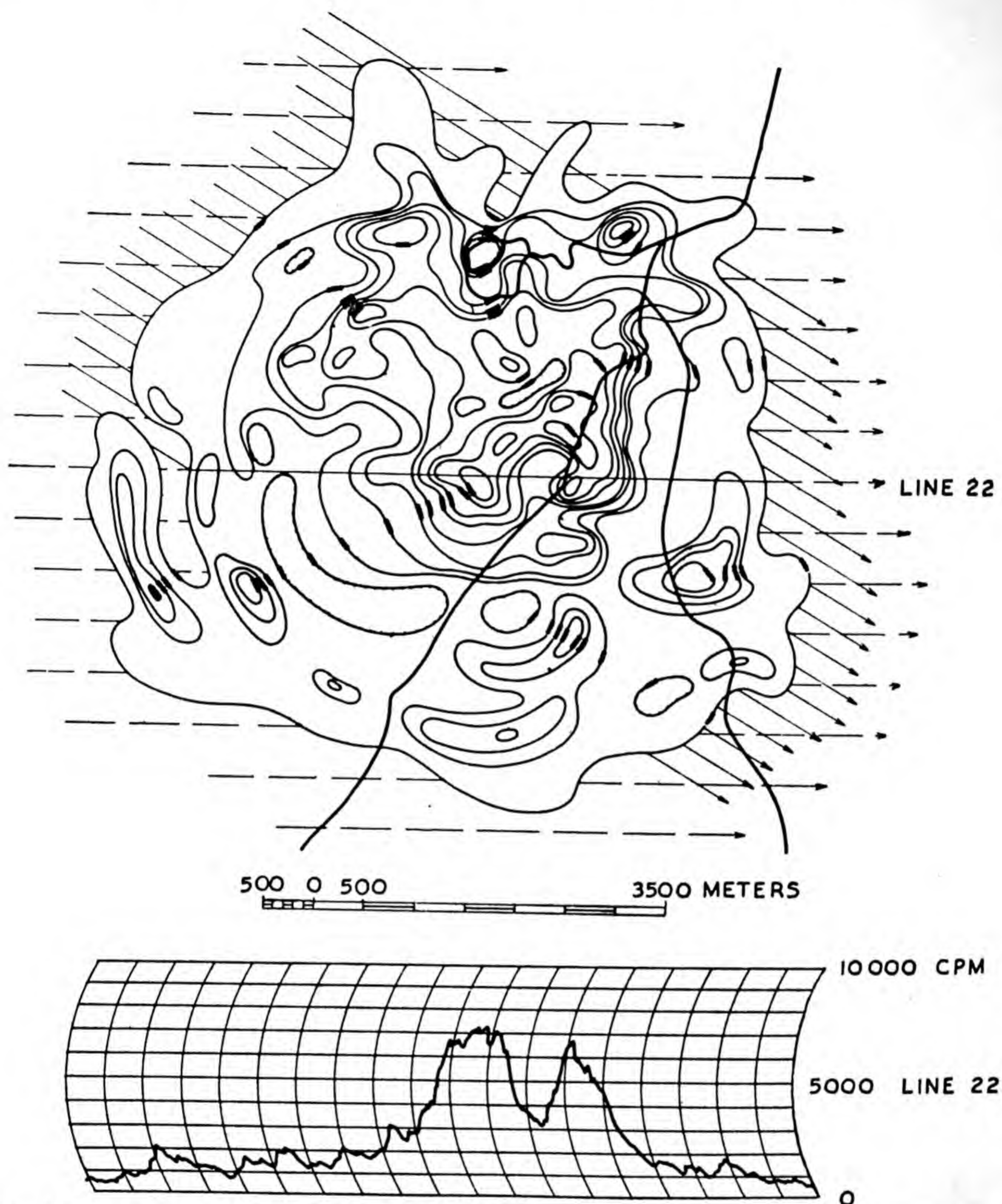


FIG. 11.7. Air-borne radiometry of an alkaline intrusive with pyrochlore mineralization.

Prior to execution of the project within which the discovery shown in Figure 11.8 was made, this anomaly of 30-km length and two other major radiation zones were detected on a preliminary "character investigation" and calibration flight over a 6000-km<sup>2</sup> block. Although some definite anomalies have been encountered of less than 1 km in detectable width, it can be assumed that systematic reconnaissance at 4 to 5 km spacing will detect a high percentage of important radiation zones.



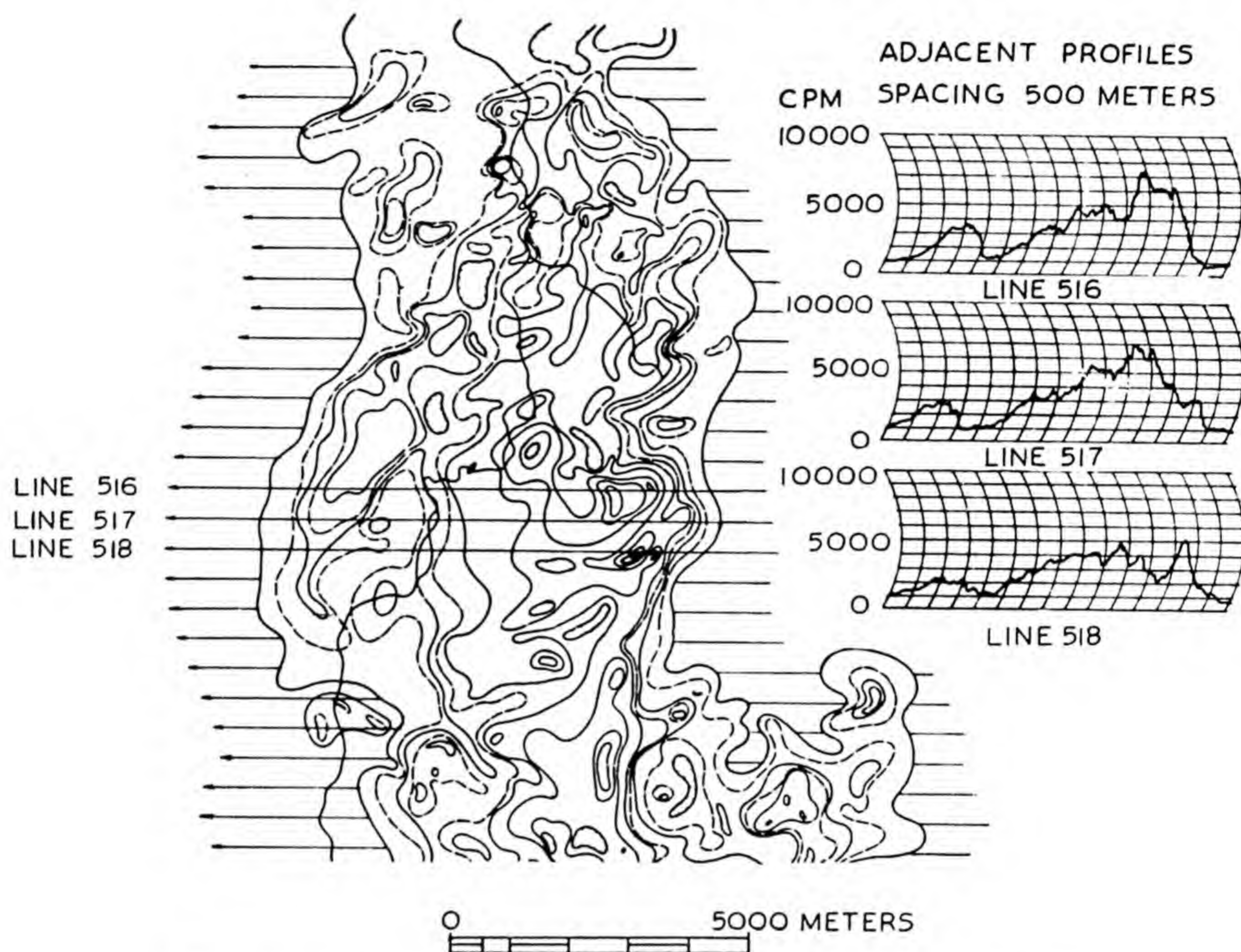


FIG. 11.8. Air-borne radiometry of a thorium-bearing gneiss.

Weather is a most important factor in the conduct of radiation surveys, whether air-borne or ground. It is known that a good deal of radiometric survey has been attempted under conditions of atmospheric and soil humidity which virtually preclude the registration of any but the very strongest direct radiation. Figure 11.9 depicts a given track, flown during a prolonged dry period and repeated on the first, second, and third day after a moderate rainfall. The drastic loss of registered intensity and gradual recovery are clearly shown.

Under the great majority of conditions, relief (proximity) effects can be kept to an insignificant level by exacting flight demands and the use of proper aircraft. Residual effects can be corrected through use of specially obtained calibration data. Figure 11.10, which demonstrates the effect of flying height on detectability, also indicates the extent to which uncontrolled variation in height above ground may distort the relative intensity measurements of an individual profile.

Air-borne magnetometry is an established geophysical tool in structural mapping and rock-type differentiation for regional geological survey. It has also proved of great value in locating and delineating radioactive anomalies as-



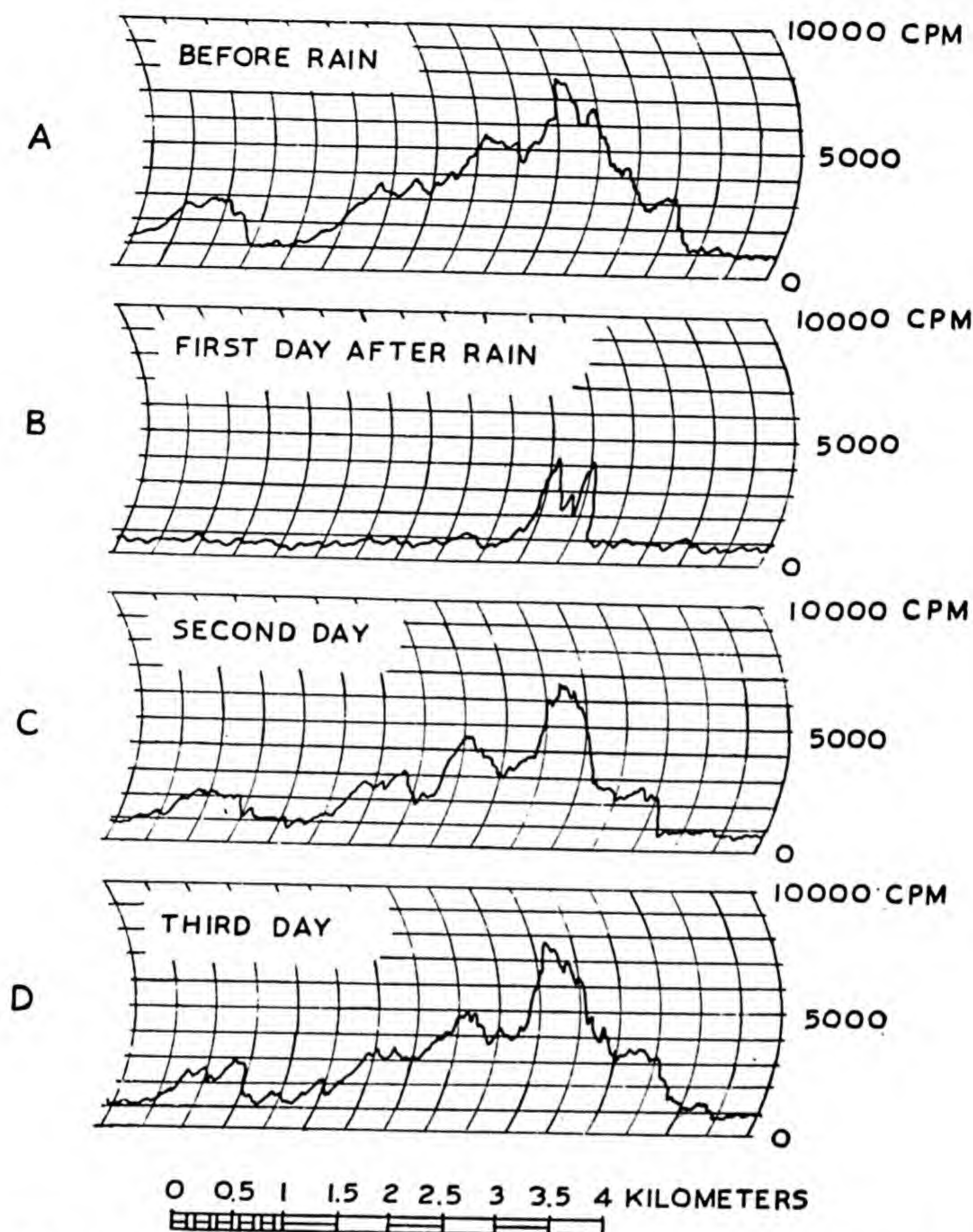


FIG. 11.9. Effect of humidity in air-borne radiometry. (A) Radiometric profile after a prolonged dry period, with detectability at a maximum. (B) One day after moderate rainfall. Note poor registration even in the strongest zone of radiation. (C) Two days after rainfall: improved registration. (D) Three days after rainfall: some areas are still masked.

sociated with alkaline type of intrusives. In preliminary investigations the magnetic pattern is frequently an important guide in assuring the examination of the whole geological unit under consideration.

Vertical air photographs are essential to navigation of dense flight patterns and to location and mapping of radiation anomalies with the accuracy needed for planning subsequent ground operations. They are equally important for field orientation of preliminary ground work.

**The classification of activity into phases.** It is evidently desirable to divide the full process into phases, and five divisions have been found to be the least



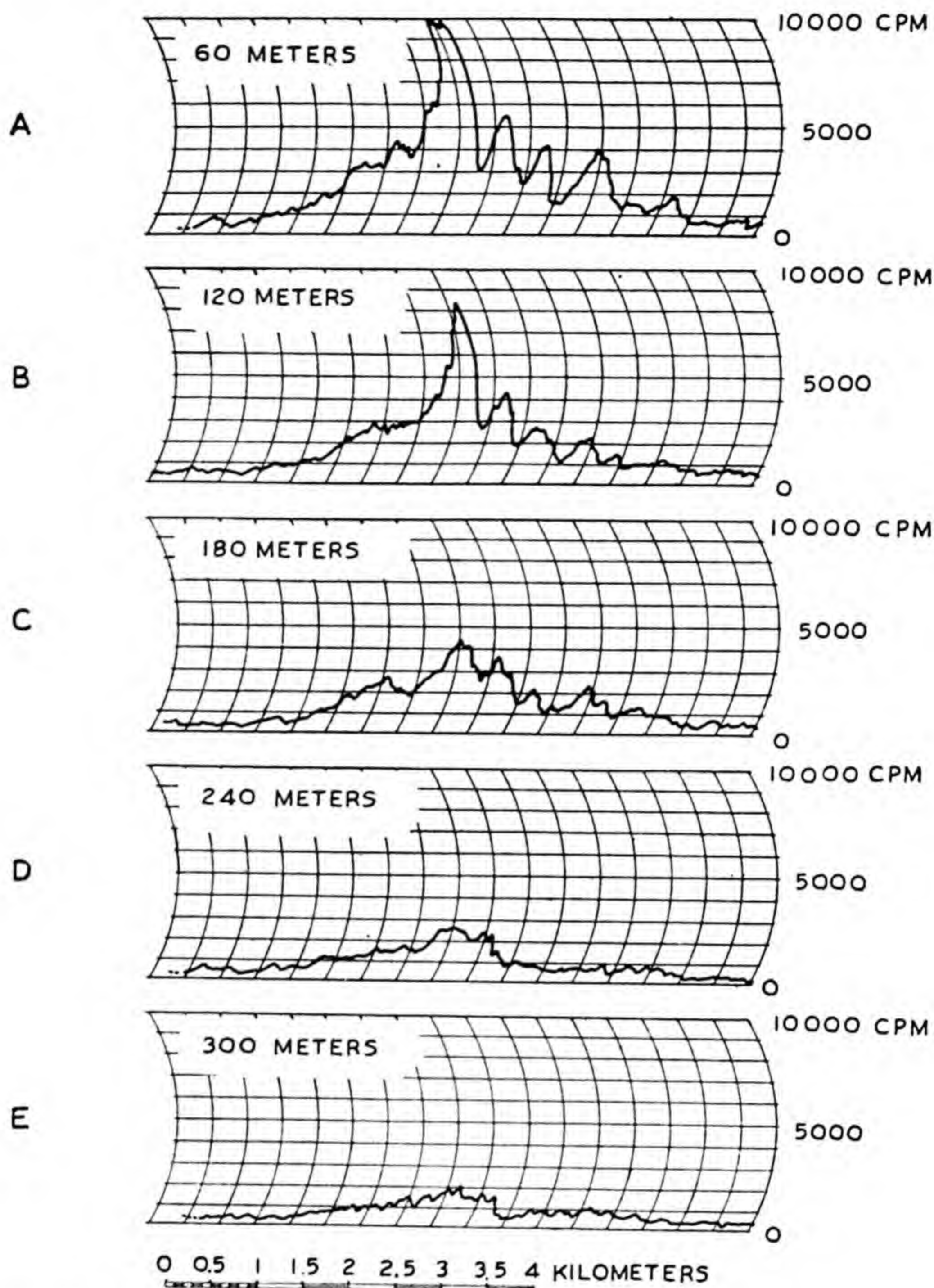


FIG. 11.10. Effect of height in air-borne radiometry. (A)–(D) The same track flown at varying heights above the terrain.

complex arrangement within which virtually all ground and air activity may be both identified and differentiated. The five phases of survey described here are not all or always essential, but represent the full range of probable activity.

#### PHASE I: RECONNAISSANCE

An air-borne operation. This is the broad coverage of the entire country, with priority on its favorable large geological units, by air-borne radiation



traverses at the widest spacing compatible with the probable detection of all major anomaly zones. Its object is to determine where to concentrate attention.

#### PHASE II: SPECIFIC INVESTIGATION

An air-borne operation. This is the specific coverage by systematic radiation profiles of known or suspected occurrences of radioactive mineral, where spacing of traverse will depend upon the nature of the occurrence. It aims at positive delineation as a basis for subsequent operations.

#### PHASE III: REGIONAL SURVEY

Air and ground operations. This is a full-fledged geological/geophysical project applicable to areas of known or probable multiple occurrence where their interrelationship will be significant. It is a basic geological survey.

#### PHASE IV: LOCAL SURVEY

Ground and air operations. This is the decisive phase of exploration operations, from which the decision to "prove" or to abandon an occurrence will usually be made. It is correctly described as detailed economic geology.

#### PHASE V: PROVING

Essentially a ground operation. This is the concretization of all factors related to the exploitation of a promising occurrence. Development decision and procedures are its end products. It may be called a mining geological survey.

In the execution of any project these inventory phases are not necessarily successive, as will be evident from their description.

Operations are normally initiated in Phase I, II, or III. For example, a reconnaissance survey over a very large area may indicate the presence of several radiation zones. Methods have been evolved for the delineation of prominent anomalies even during the reconnaissance flights, and the specific investigation of these may actually take place at the earliest stage of discovery. On the other hand successful Phase II investigations have been conducted as a result of bibliographic selection of favorable local situations, or following inconclusive ground indications. Comprehensive regional geological/geophysical surveys, of the Phase III type, justified by general knowledge or with other geological aims, have resulted in a number of important discoveries.

The confirmation of a positive radiation anomaly, combined with what is known of its circumstance, results in classification of the discovery and the



decision to pursue its possibilities, usually in the "natural" succession shown diagrammatically. However, in some cases it is found technically or economically advisable to select a different evaluation course—for example, turning back, at some point in a local, Phase IV survey, when it becomes evident that available basic geology is inadequate or that a series of occurrences should be interrelated.

**Some fundamentals of air-survey technique.** Flight altitude must take into account aircraft limitations as well as the advantages of proximity for detection. Heights from 100 to 150 meters above terrain have been found to be feasible from a flying point of view, except under the severest conditions of relief, when 200 meters ground clearance has occasionally been resorted to. From Figure 11.10 it may be seen that discrimination drops off rapidly above 200 meters, and that at higher altitudes the detail of important low-intensity radiation may be lost in background variations.

Flight spacing is related to flying height through the detector's "viewing" angle. Interpolation between profiles is minimized with a flight spacing of two-thirds of the ground clearance. Only in the most detailed surveys is this optimum attempted, flight spacings up to about three times ground clearance being commonly used. Lateral detection, for reconnaissance surveys with wide flight spacing, can be increased by lowering of the detecting crystal in its shielding cylinder.

Planning of operations is closely linked with assumed or known geological conditions. It is evident that the survey of Figure 11.11 would have been considerably less effective if its flight direction had been parallel to the shore line. A systematic survey of a series of parallel pegmatite dykes would logically be conducted at right angles to their trend, and later intensification flights might follow anomalous indications. It is perhaps sufficient to state that operations planning is very much a geologist's job.

The carrying aircraft may be of almost any type, but few are truly adaptable to the wide range of flight conditions encountered. For certain local, detailed surveys a light aircraft has been found suitable, but the broader inventory type of operations call for a large, stable aircraft, with long range, low speed, stability in turbulence, and high maneuvering performance.

The importance of the carrying aircraft is realized best, indirectly, on examination of the profiles of Figure 11.10, which show the effect of height on detectability of radiation. Flying is normally at 150 meters above terrain, and this height must be maintained to close tolerances, regardless of relief and aircraft attitude. Continuous 200–300-meter terrain variations are frequently met, and for systematic surveying, the heavy aircraft, with an excess of power and wide permissible speed range, becomes essential.

For surveys of the Phase III and IV types, it is necessary to have vertical photographs for flight navigation. The Phase I reconnaissance profiles may be



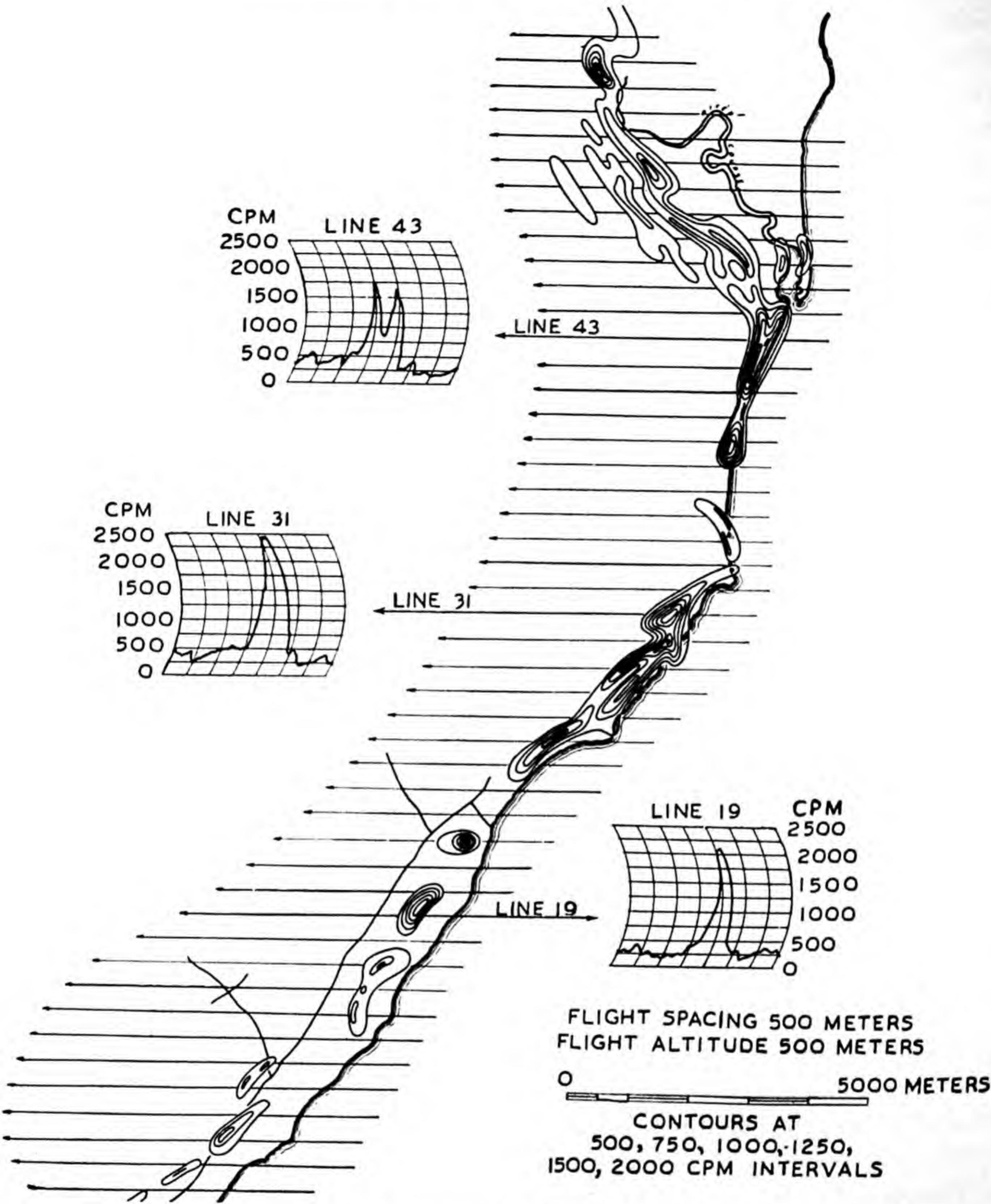


FIG. 11.11. Air-borne radiometry of coastal monazite deposits.

flown on existing maps and the Phase II investigations may be carried out by timed runs and systematic turns which form a network, but these latter flights will later require air photographs for accurate plotting of profiles.

Particularly during major operations which involve the integration of a large number of flights, it is exceedingly important that detecting equipment be properly calibrated, and that for every flight a conclusive air-borne test run



be carried out to confirm that instrument operation and atmospheric and ground conditions are consistent with the standards set for the particular project. The practice of periodic repetition of flights over a positive radiation anomaly has been adopted, wherever feasible, as a supplement to the more difficult and critical routine checks of background over a test line.

For Phase II investigations and for regional surveys, magnetic and radiation detection may often be simultaneous. Fortunately, the flight techniques of radiometry are almost entirely compatible with magnetic requirements, which therefore place no important restriction on the principal operation. A relatively heavy aircraft is essential as a platform for the magnetometer.

**Results of typical air-borne radiometric surveys.** It should be noted that radiation profile cpm scale varies in the examples that are shown.

Figure 11.11 is the radiometric mapping of a well-known monazite-bearing coastal strip. A scintillation survey at 500 meter spacing at right angles to deposit trends located and outlined all known occurrences, registered intensities in surprisingly accurate proportion to the known quantities of monazite lying about one meter below the surface, and effected a completely new discovery within a short distance of previous intensive ground prospecting. The survey is unique in having precisely indicated the presence of some bags of concentrate in a field storehouse.

Figure 11.12 is the radiometric mapping of an occurrence of uraniferous zirconium and a nearby thorium/rare earth deposit in an alkaline province. An interesting contrast of radiation intensity is shown, the alluvial zirconium/uranium producing relatively weak, scattered anomalies. This Phase II investigation was initiated with limited knowledge of the radioactive character of the zirconium deposits, and sensitivity and recording scale were adapted to the weak radiation encountered over a known occurrence. As a result, two thorium/rare earth deposits, within a few kilometers and exhibiting much stronger radiation, were recorded "off scale" as seen in Figure 11.12.

Figure 11.7 is the radiometric mapping of a highly concentrated occurrence of columbium-pyrochlore. Flights at 250-meter spacing, integrated with crossing flights at 500-meter spacing, have discriminated in considerable detail the surface exposure of the pyrochlore, and numerous peripheral anomalies. This survey is especially noteworthy in that the presence of the thorium/uranium/rare earth-rich mineralization, was discovered during a specific investigation of a known radioactive apatite formation about 2 km distant. Both occurrences are within the same major anomaly. Radiation is relatively weak over the apatite zone, but reaches 23 times background over the pyrochlore, with normal instrument settings.

Figure 11.8 is the radiometric mapping of half of a large anomaly caused by multiple veins of a thorium/rare earth-bearing mineral in a gneissic rock. This anomaly, continuous over 240 km<sup>2</sup>, was mapped during a Phase III



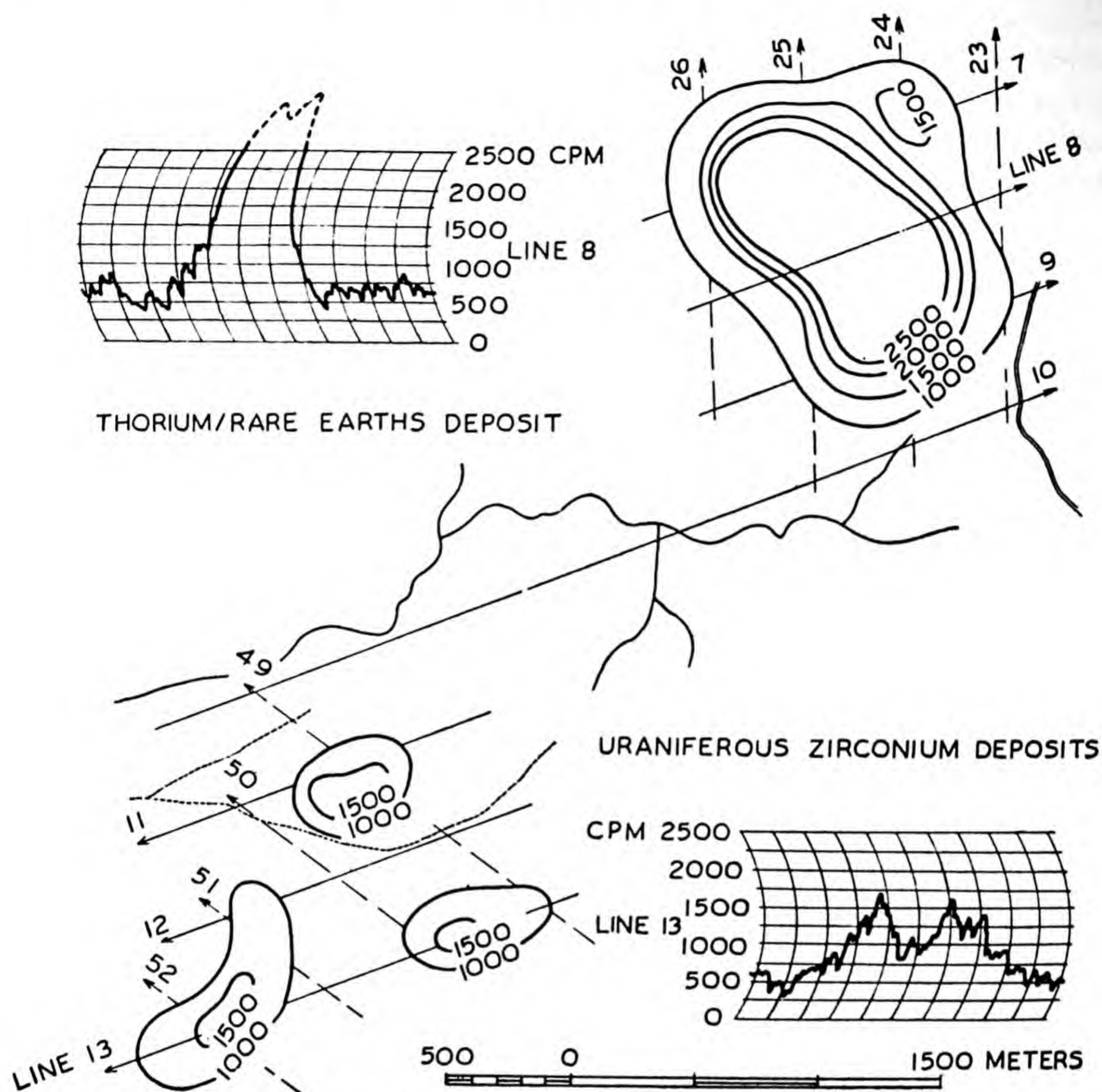


FIG. 11.12. Air-borne radiometry of uraniferous zirconium and thorium/rare earths deposits.

regional survey of an area considered favorable geologically to radioactive mineral occurrence.

Figure 11.13 is the radiation mapping of two syenite intrusives encountered during a Phase III type of survey with general geological purpose. The radioactive mineral has not yet been identified.

Figure 11.14 is the aeromagnetic mapping of the columbium-pyrochlore-bearing intrusive of Figure 11.7, demonstrating an association which has proved common to several other similar occurrences and aided not only in their discovery but in structural determinations of great value in later operations. The limit of significant radiation is shown by a heavy broken line.

The pattern of magnetite concentration in the intrusive was determined



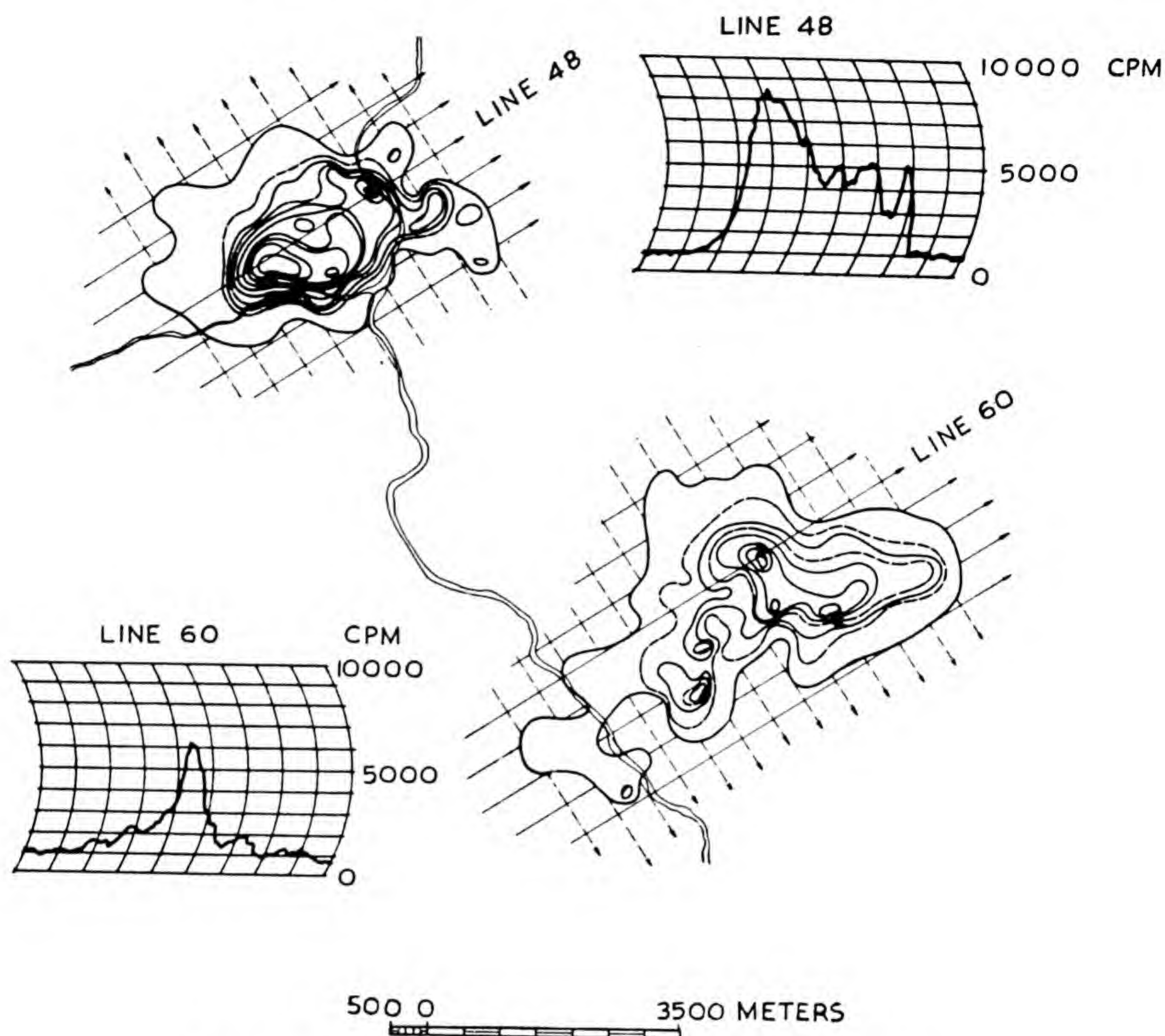


FIG. 11.13. Air-borne radiometry of syenite intrusives.

from second derivative mapping of the total field magnetic measurements illustrated. An evident relationship between magnetite distribution and radiation intensity led to the establishment by simple analysis of a quantitative correlation between magnetite and pyrochlore in the rock. As a result, both types of air-survey data have been most useful in the planning of drilling and other proving operations.

Radiometric maps of the types shown are the principal product of their respective air-borne surveys. Whether they are rough indications such as the investigation in Figure 11.12, or detailed and precise as in the project of Figure 11.7, these maps and the topographic and geological data with which they are closely integrated are highly significant steps in the sequence of location, identification, and evaluation.

**Conclusions.** When it is realized that the discoveries of radioactive minerals discussed in this paper represent less than one-half of the successful search



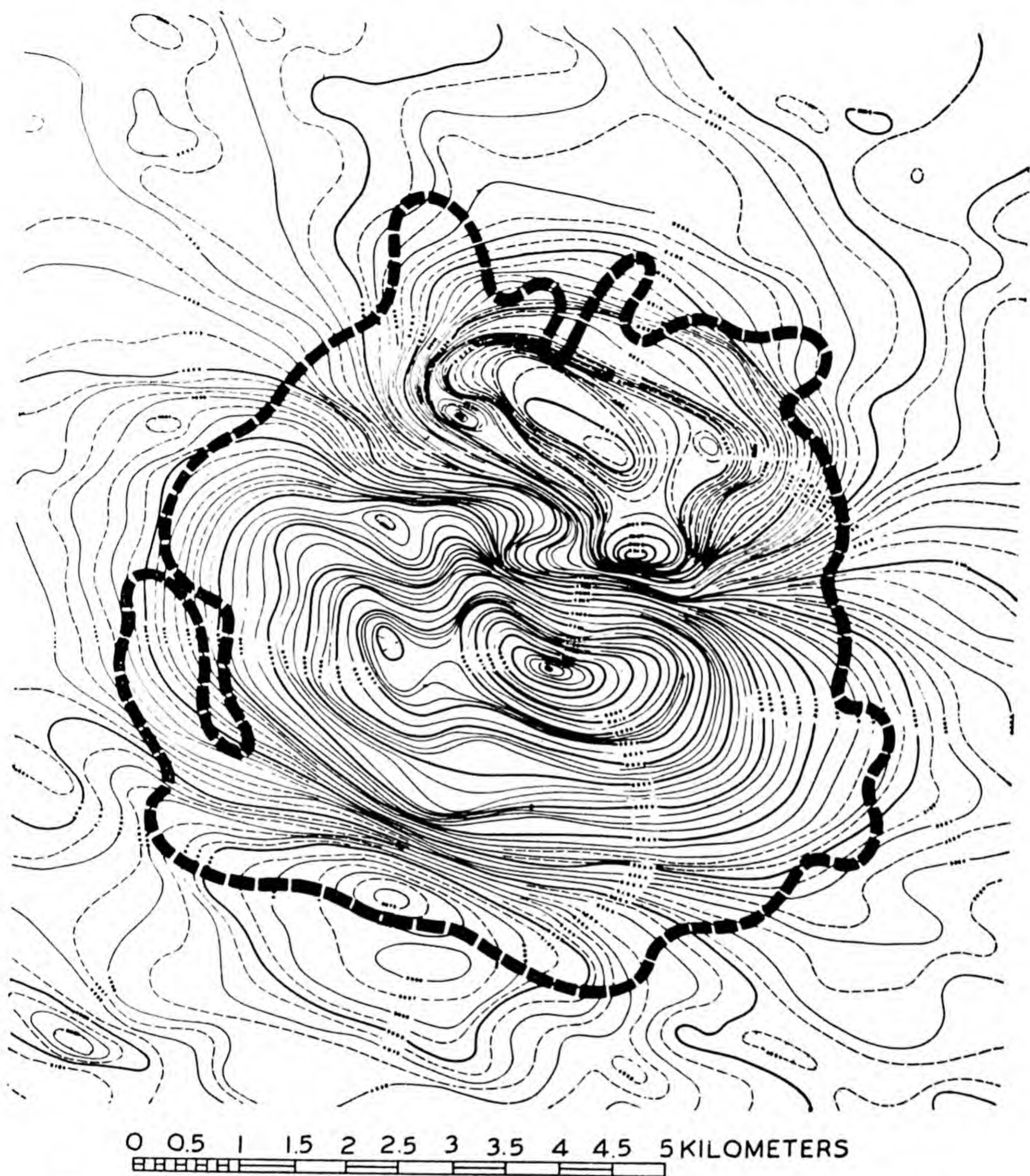


FIG. 11.14. Air-borne magnetometry of alkaline intrusive shown in Fig. 11.7.

carried out by a single geophysical flying unit, operating intermittently during an eighteen-month period, the significance of air survey to the "atomic" future of Brazil may be assessed.

The current market value of the already proved reserves of an associated mineral discovered by one of the surveys demonstrated here, amounts to five thousand times the whole cost of all operations, air and ground, of the surveying organization during the eighteen-month period of the explorations. By



implication, an inventory of raw materials for atomic-energy production in Brazil will finance itself.

#### AERIAL RADIOMETRIC PROSPECTING IN CANADA \*

In 1946 Eldorado Mining and Refining, Ltd., obtained the assistance of the National Research Council in beginning a joint air-borne research project. A few test flights were made by Eldorado personnel in 1947 and 1948, which indicated that Geiger counters were preferable to ionization chambers. In 1948 the development of an air-borne scintillation counter was begun. In 1949 the two organizations mentioned above were joined by the Geological Survey of Canada and the Royal Canadian Air Force in an expanded project to try to develop air-borne methods for both preliminary reconnaissance of large areas and detailed prospecting of small areas. Further tests of ionization chambers and multiple-tube Geiger assemblies were performed. These were unsatisfactory, so work was concentrated on the design of a more sensitive scintillation counter. In 1950 three shielded scintillation probes were mounted in the aircraft in an attempt to provide better discrimination between small and large sources of radioactivity, and extensive tests were made at a height of 500 feet above terrain; but all anomalies investigated proved to be large areas of weakly radioactive rock. The larger joint project was abandoned, but the Eldorado company and the Geological Survey continued to experiment. Scintillation counters were built for use in a "bird" towed beneath a conventional aircraft and in a helicopter, and were tested in 1953. It was hoped that discrimination between small and large sources might be obtained by comparing readings from a counter in a "bird" and one in the aircraft, but this gave no improvement over the former method. Experiments by Eldorado with a low-flying helicopter for prospecting a large group of claims were fairly successful, and this work was continued in 1954. The Geological Survey is continuing to use air-borne scintillation counters in conventional aircraft in connection with its aeromagnetic surveys, and in helicopters in northern Canada.

In both the work done by private organizations and that done by Eldorado with helicopters it has been concluded that best results are obtained by flying irregularly from outcrop to outcrop, and keeping at a constant height above the ground, rather than by flying on straight lines and at a constant altitude above sea-level; it has also been found that an aural signal is desirable to notify the observer of an anomaly, and that it is desirable for the observer to be an experienced geologist who can make geological observations, attempt to discriminate from the air the source of the anomaly, and land nearby for an inspection if that seems warranted.

\* From Geneva Conference Paper 1, "Uranium Prospecting in Canada—Ground and Aerial Surveys" by A. H. Lang, Geological Survey of Canada.



In summary, it appears that the Canadian Shield presents unusual difficulties for air-borne prospecting for radioactive deposits because it contains many exposures of weakly radioactive rocks and many insignificant pegmatitic occurrences. These cause a background such that anomalies from significant deposits are overwhelmed and difficult to detect except at low altitudes. These problems may not be so serious for some other regions, but to date little air-borne work has been done in Canada for uranium except over the Shield. For work in the Shield, either conventional aircraft or helicopters show promise for detecting fairly extensive deposits, but only helicopters, very low-flying conventional aircraft, or "birds" towed at a very low height seem suitable for the detection of small exposures such as those of veins, and then only if the aircraft passes less than 150 feet horizontally from the exposures. Helicopters appear to have the advantages of greater safety at low altitudes, of being able to fly very slowly to permit visual observation, and of being able to land on or close to many (but by no means all) outcrops whose examination is desirable.

#### SELECTED REFERENCES FOR CHAPTER 11

- Agocs, W. B., 1955: Airborne scintillation counter surveys. *Bull. Can. Inst. Min. & Met.* March, 1955, pp. 109-111.
- Brownell, G. M., and R. J. R. Schaller, 1954: Prospecting local areas with the airborne scintillometer. *Precambrian* 27:6-11.
- Cook, J. W., 1952: An analysis of airborne surveying for surface radioactivity. *Geophysics* 17:687-706.
- Cowper, G., 1954: Aerial prospecting with scintillation counters. *Nucleonics* 12(3):29-32.
- Fano, W., 1953: Gamma ray attenuation. *Nucleonics* 11(8):8-12, and 11(9):55-61.
- Foote, R. S., 1954: Airborne exploration for uranium. *Mines Mag.* 54(10):31-32.
- Godby, E. A., and others, 1952: *Aerial Prospecting for Radioactive Minerals*. Chalk River, Ontario, National Research Council of Canada, Report No. CRR-495.
- Goldstein, H., and J. E. Wilkins, 1954: *Calculations of the Penetration of Gamma Rays: Final Report*. U.S. Atomic Energy Commission Report NYO-3075.
- Gregory, A., 1955: Aerial detection of radioactive mineral deposits. Paper presented at annual meeting, Canadian Institute of Mining and Metallurgy, April, 1955. To be published in *Can. Inst. Min. & Met. Bull. & Trans.*
- Moxham, R. M., 1954: *Airborne Radioactivity Surveys for Phosphate in Florida*. U.S. Geological Survey Circ. 230.
- Pedersen, Ole, 1954: *Mathematical evaluation of airborne radiological survey data*. U.S. Atomic Energy Commission Report NYO-4577.



# *Chapter 12*

---

## GEOPHYSICAL PROSPECTING \*

---

### THE COLORADO PLATEAU REGION

Uranium deposits are widely scattered over the Colorado Plateau region of Colorado, New Mexico, Arizona, and Utah. The major uranium-bearing formations are the Shinarump conglomerate and the Chinle formation of Late Triassic age, and the Entrada sandstone, the Todilto limestone, and the Morrison formation of Late Jurassic age. The deposits in the Shinarump and Morrison have been the chief target of the geophysical methods. The Morrison formation in western Colorado consists of the upper Brushy Basin and lower Salt Wash members. The Brushy Basin member consists of alternating layers of sandstone and shale, and the Salt Wash member consists of beds of sandstone separated by mudstone splits. The uranium deposits of the Morrison are commonly found in the sandstone strata of the Salt Wash member as thin, irregular, tabular layers ranging in width from a few feet to several hundred feet. Their lateral distribution is irregular, and they tend to occur as clusters. The ore-bearing sandstone is commonly lenticular, is interbedded with mudstone, and in many places contains mudstone splits. The most favorable geologic conditions for the occurrence of uranium deposits in the Salt Wash sandstone member are considered to be the thickening of the lenticular sandstone, pale-brown to light-brown color of the sandstone, and presence of altered gray-green mudstone underneath the Salt Wash member. In the unfavorable areas the sandstone is thin, contains many mudstone splits, is red-brown in color, and is underlain by red-brown mudstone.

The Shinarump conglomerate varies in composition from a fine-grained sandstone to a coarse conglomerate, is usually crossbedded, contains local lenses of shale and mudstone and much silicified wood. The Shinarump conglomerate unconformably overlies the Moenkopi formation of early and

\* From Geneva Paper 514, "Geophysical Exploration for Uranium on the Colorado Plateau" by R. A. Black, U.S. Geological Survey. Selected references are listed alphabetically at the end of the chapter.



middle(?) Triassic age. The Moenkopi is composed of thin, hard, red shales, red sandy mudstones and siltstones, and occasional layers of sandstone. The top of the Moenkopi formation is generally considered to be an erosion surface over which the conglomerates and sandstones of the Shinarump are spread. The Shinarump uranium deposits occur mainly in channel fillings in the Moenkopi formation, particularly where the channels contain carbonaceous matter and mudstone beds. The Shinarump conglomerate in turn is overlain by the Chinle formation which consists of a thick series of mudstones, sandstones, and conglomerates.

Since 1949 the applicability of many geophysical techniques to the search for uranium have been tested. These techniques include magnetic, electrical resistivity, natural potential, electric logging, seismic refraction and reflection, and surface-inhole electrical methods. The methods have been tested by making measurements over known Morrison and Shinarump ore deposits and over terrain known to be favorable for ore deposition, first in areas where the Salt Wash sandstone member and the Shinarump conglomerate were exposed at the surface, and then in areas where the Salt Wash and the Shinarump are overlain by rocks of different thicknesses and types. The various exploration methods were then used in areas which were geologically similar to those in which the particular method had been demonstrated to be successful.

#### SURFACE ELECTRICAL METHODS

**Electrical-resistivity methods.** Electrical-resistivity methods were among the first geophysical methods tested on the Colorado Plateau. Tests of the resistivity method were made over known ore bodies in the Salt Wash member during 1949–1950. During 1951–1952 several electrical-resistivity surveys were made to map favorable ground prior to drilling. In 1952 the electrical-resistivity method was successfully applied to the problem of locating buried Shinarump-filled channels.

Measurements were made with direct-current equipment and nonpolarizable electrodes; both the vertical and horizontal profiling techniques with the Lee partitioning configuration were used. In vertical profiling the electrode configuration is expanded outward from the station center, using increasing increments of electrode spacing. In horizontal profiling, several profiles are made with different electrode spacings, and when the optimum spacing is determined, this spacing is then used for the remainder of the profiles. The field procedures used on the Colorado Plateau are substantially the same as those in common use throughout the arid sections of the world. One of the biggest problems is that of making satisfactory electrode contact with the earth. In many places on the Colorado Plateau the surface consists of thin, sandy alluvium overlying sandstones and shales which occasionally crop out at



the surface. The potential electrodes are usually placed in shallow water-filled holes to establish a moist contact zone between the potential electrodes and the earth. In areas of exposed bedrock, small sections of copper screening covered with earth and saturated with water are used for potential electrodes. In areas of poor electrode contact it is necessary to balance the current electrode contact resistances to get reliable data.

The electrical-resistivity methods used on the Colorado Plateau have been primarily concerned with exploration for uranium deposits in the Morrison formation and in the Shinarump conglomerate. In areas where the deposits are in the Morrison formation, the resistivity depth-profiling method proved capable of delineating the thick and thus more favorable parts of the ore-bearing Salt Wash member in areas where the member was not overlain by thick sections of the Brushy Basin member of the Morrison formation. The resistivity depth curves could be used to determine the relative thickness of the ore-bearing sandstone and the relative amounts of mudstone present in the sandstone. In general, the thicker, more favorable parts of the ore-bearing sandstone exhibited a higher resistivity than did the unfavorable sandstone. By making several vertical depth profiles on a grid pattern and evaluating each profile as favorable, semifavorable, or unfavorable on the basis of the indicated thickness of sandstone, amount of mudstone in the sandstone, and the resistivity of the sandstone, maps could be prepared showing the areas considered favorable, semifavorable, and unfavorable. Resistivity horizontal profiles were also made to detect the favorable spots to drill for uranium deposits. The thicker, more favorable parts of the ore-bearing sandstone could often be found as zones of anomalous high resistivity on the horizontal profiles.

Shinarump-filled channels are the principal target for resistivity surveys made to guide exploratory drilling for uranium deposits in the Shinarump. The resistivity of the Shinarump conglomerate is 10 to 100 times as great as that of the underlying Moenkopi shales and siltstones, and thus provides a satisfactory electrical contrast between the two stratigraphic units.

A combination of vertical and horizontal profiling techniques is usually used in surveys to locate the buried channels. The size of the channels may vary over a considerable range but an average channel is of the order of 100 to 200 feet wide with a depth of scour of 20 to 100 feet. In areas where there are no channels the Shinarump conglomerate is some 20 to 100 feet thick.

Figure 12.1 shows electrical-resistivity depth curves and the resistivity horizontal profile over a Shinarump channel. The depth curves and the horizontal profile show definite evidence of the buried channel. Methods used to interpret the depth curves range from matching the field curves to theoretical two- and three-layer curves, to simply correlating changes in curve character with known geology and extrapolating into unknown areas. The horizontal profiles are plotted as the ratio of the differences to the sum of the resistivities on either side of the Lee partitioning configuration. The area between the



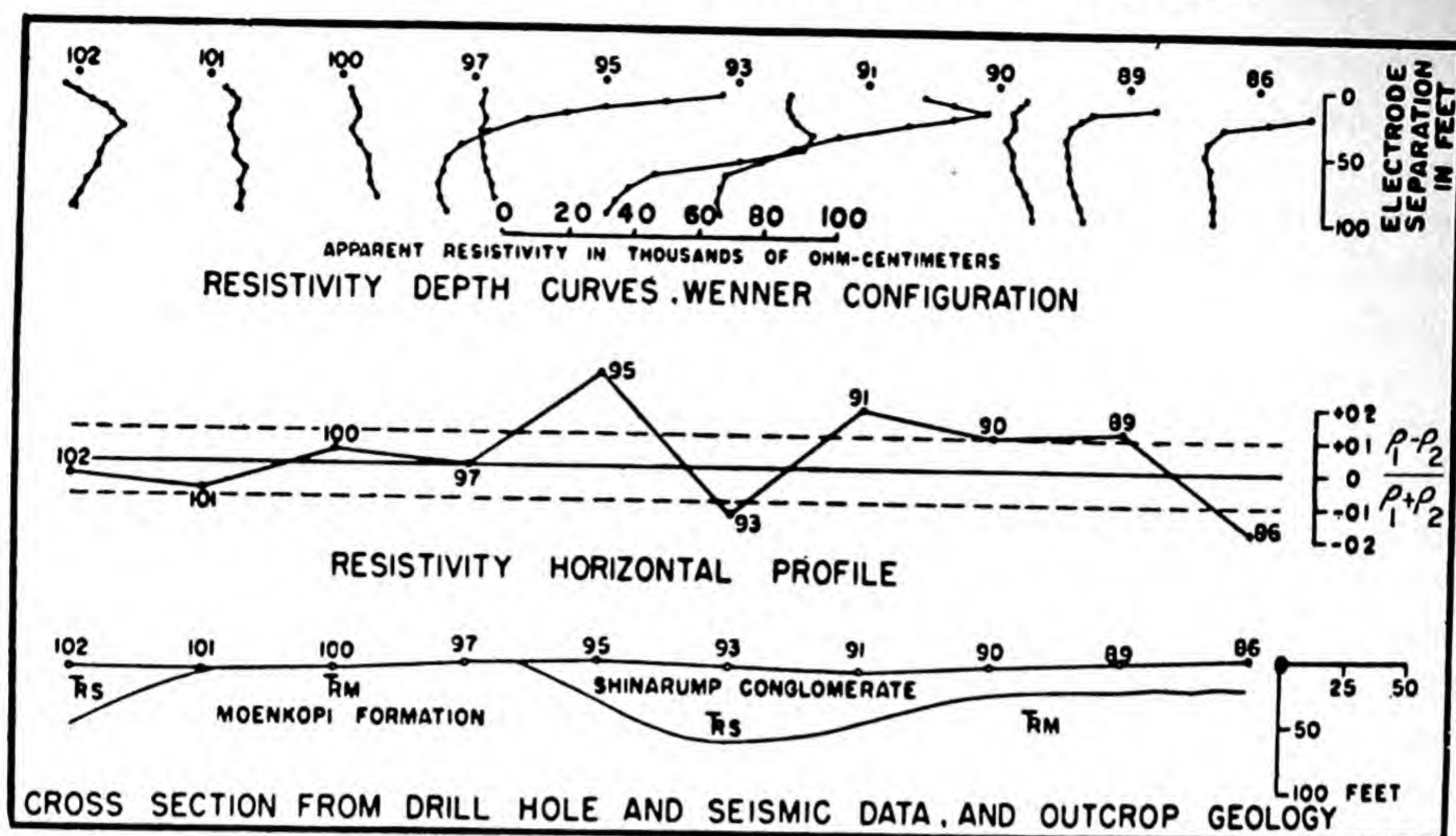


FIG. 12.1. Electrical-resistivity depth curves and horizontal profile over Shinarump channel.

dashed lines represents "background noise" due to surface lateral variations and contact resistances. Figure 12.2 shows a number of resistivity horizontal profiles, made at an electrode separation of 60 feet, over known Shinarump channels and a profile over a nonchannel area for comparison.

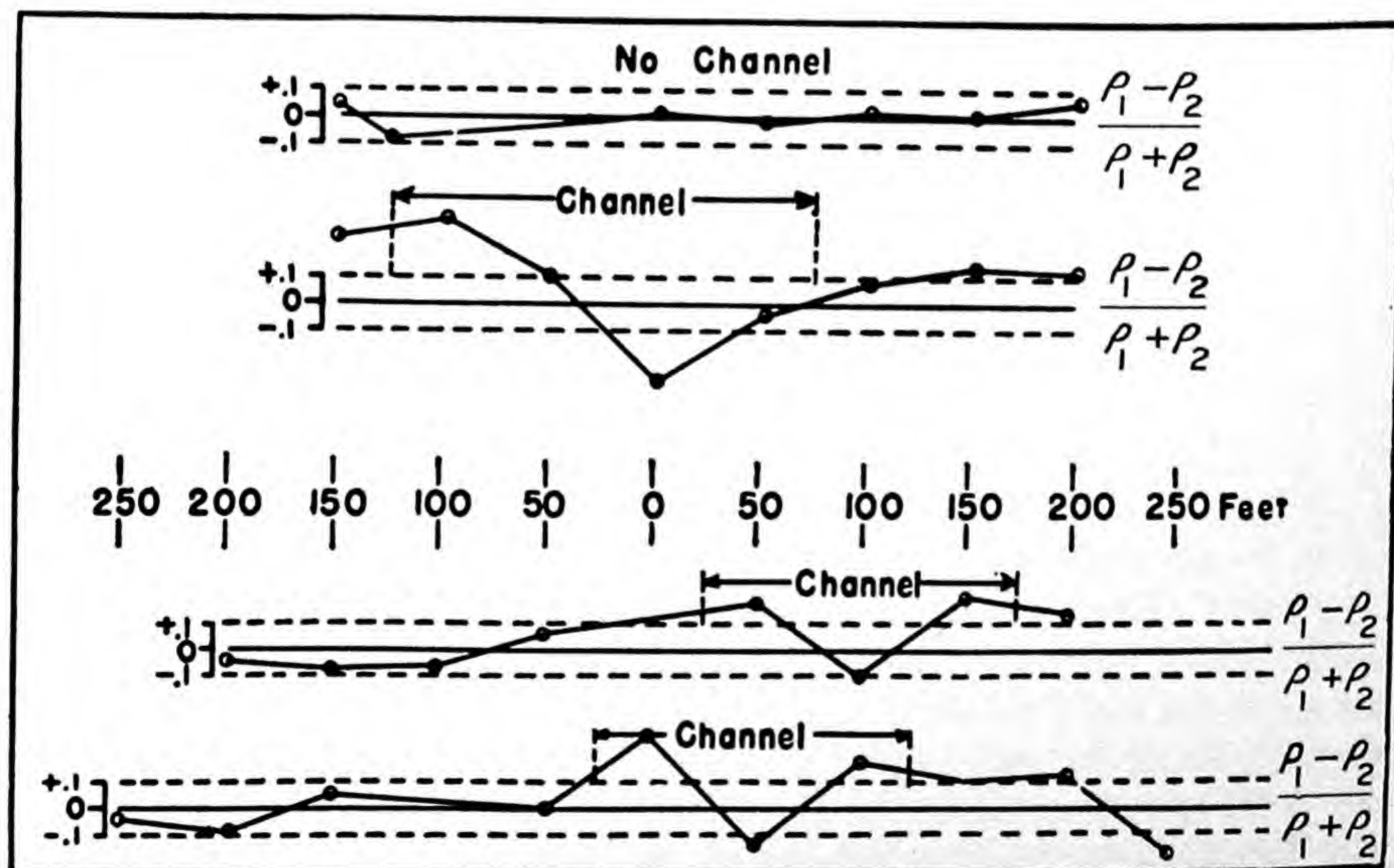


FIG. 12.2. Electrical-resistivity horizontal profiles over Shinarump conglomerate, Monument Valley, Arizona.



**Natural potential.** The natural potential method, where applicable, is undoubtedly one of the cheapest and most rapid methods of exploration for shallow ore deposits. Natural-potential methods have for this reason been extensively tested in various areas of the Colorado Plateau. Measurements have been made over uranium ore bodies buried at shallow depths and known to be undergoing active oxidation, but in general, no significant natural-potential anomalies have been detected over these ore bodies.

### SEISMIC METHODS

**Refraction surveys.** The seismic-refraction method was first used for mapping buried channels in exploration for uranium on the Colorado Plateau by Wantland and Casey of the U.S. Bureau of Reclamation. Additional field tests were made by the U.S. Geological Survey in 1953. These tests showed that the seismic-refraction method could be used to locate buried Shinarump-filled channels where there was no Chinle overburden, and during 1953 and 1954 numerous seismic-refraction surveys were made in Monument Valley, Arizona, to outline major channel trends prior to exploration drilling.

The seismic-refraction measurements were made with standard portable seismograph equipment, installed in a four-wheel-drive vehicle to permit more rapid coverage of rough areas.

The method of continuous profiling with reversed shots was used in making the seismic-refraction surveys. To map the average Shinarump channel, shot points were 500 feet apart and the geophones were spaced at 25- and 50-foot intervals. Air shooting was extensively used for the refraction seismic work. Single charges of 5 to 10 pounds of 60% seismic dynamite were fired from special shooting poles at heights of 3 to 5 feet above the ground. The records obtained from these air shots were comparable to those obtained from hole shots, and air shooting proved to be more economical because of its greater speed.

Inhole-velocity surveys were usually made to provide advance information on velocity characteristics of the formations to be investigated. These inhole-velocity measurements were made with inhole piezoelectric detectors and surface shots.

To date, use of the seismic-refraction method on the Colorado Plateau has been restricted to the problem of locating buried Shinarump-filled channels. The velocity in the Shinarump conglomerate ranges from 3000 to 6000 fps, and in the underlying shale of the Moenkopi the velocity is 10,000 to 15,000 fps. Figure 12.3 shows a series of time-distance plots drawn from records obtained by continuous profiling and reverse shooting.

The method of interpreting the seismic data is a modification of a method suggested by A. J. Barthelmes for calculating the depth to curved surfaces



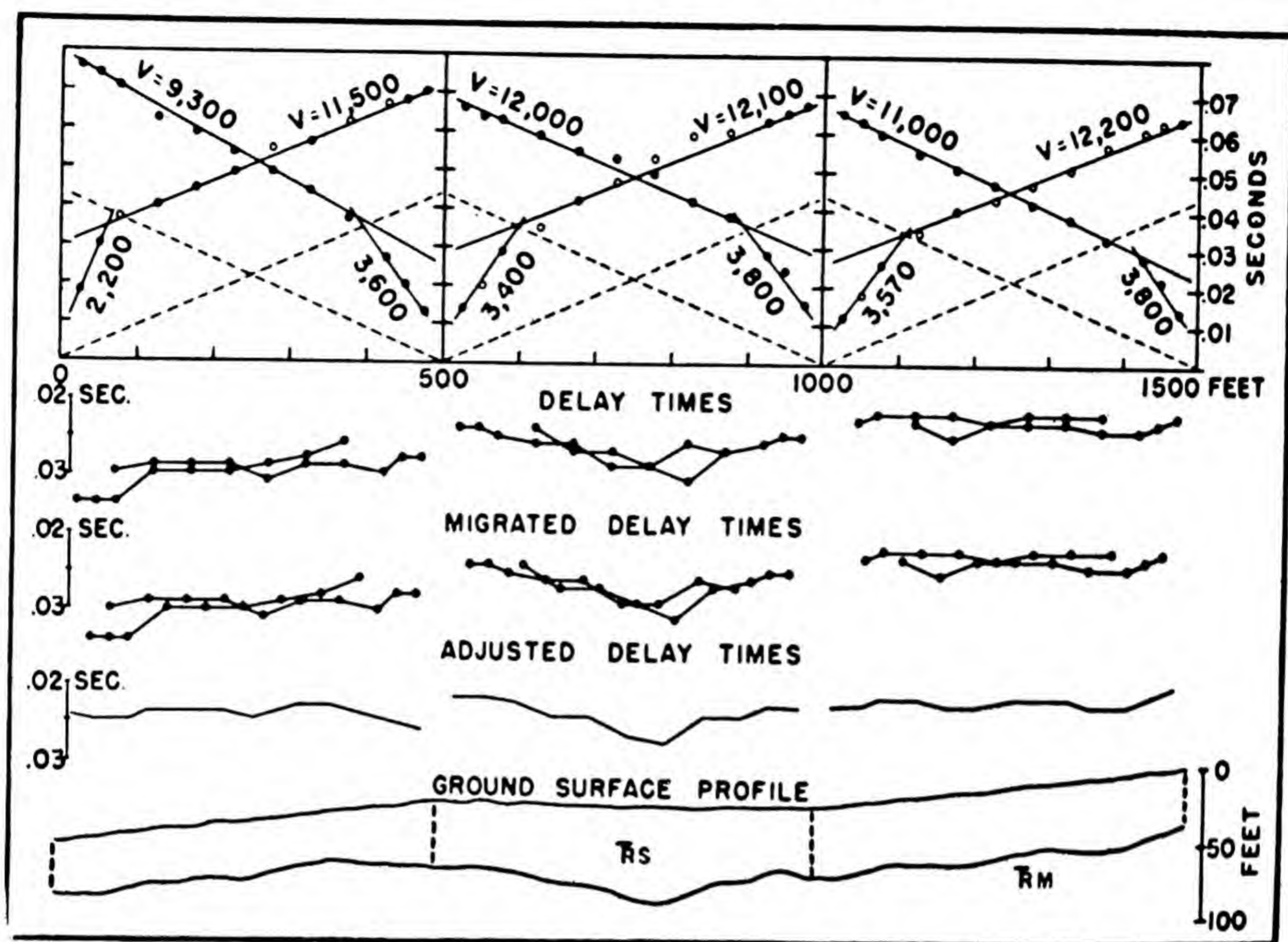


FIG. 12.3. Time-travel plots, delay times, and corresponding geologic cross section.

by the use of delay times. Depths to the Shinarump-Moenkopi contact at each shot were computed by conventional critical-distance or time-intercept methods. The dashed lines on the time-distance plots represent an average velocity in the Moenkopi in this area. Using this average velocity line and the apparent Moenkopi velocity line, delay times were plotted as shown. These delay times were migrated toward their respective shot points and then averaged. The adjusted delay time curves for the zones between the shot points were converted to differential depths, and using the shot-point depth computations as control, the topography of the Shinarump-Moenkopi contact was determined. In this particular instance, a small channel was revealed that did not show from the computed shot-point depths alone.

Figure 12.4 is a subsurface contour map of the Shinarump-Moenkopi contact in an area in Monument Valley, Arizona. A channel clearly indicated by the seismic data was verified by subsequent drilling in this area.

**Shallow-reflection surveys.** In the summer of 1954, experimental shallow-reflection measurements were made to determine if usable shallow reflections could be obtained under the stratigraphic conditions present on the Colorado Plateau. The equipment used to make these experimental measurements consisted of a 12-channel portable reflection seismograph with high frequency



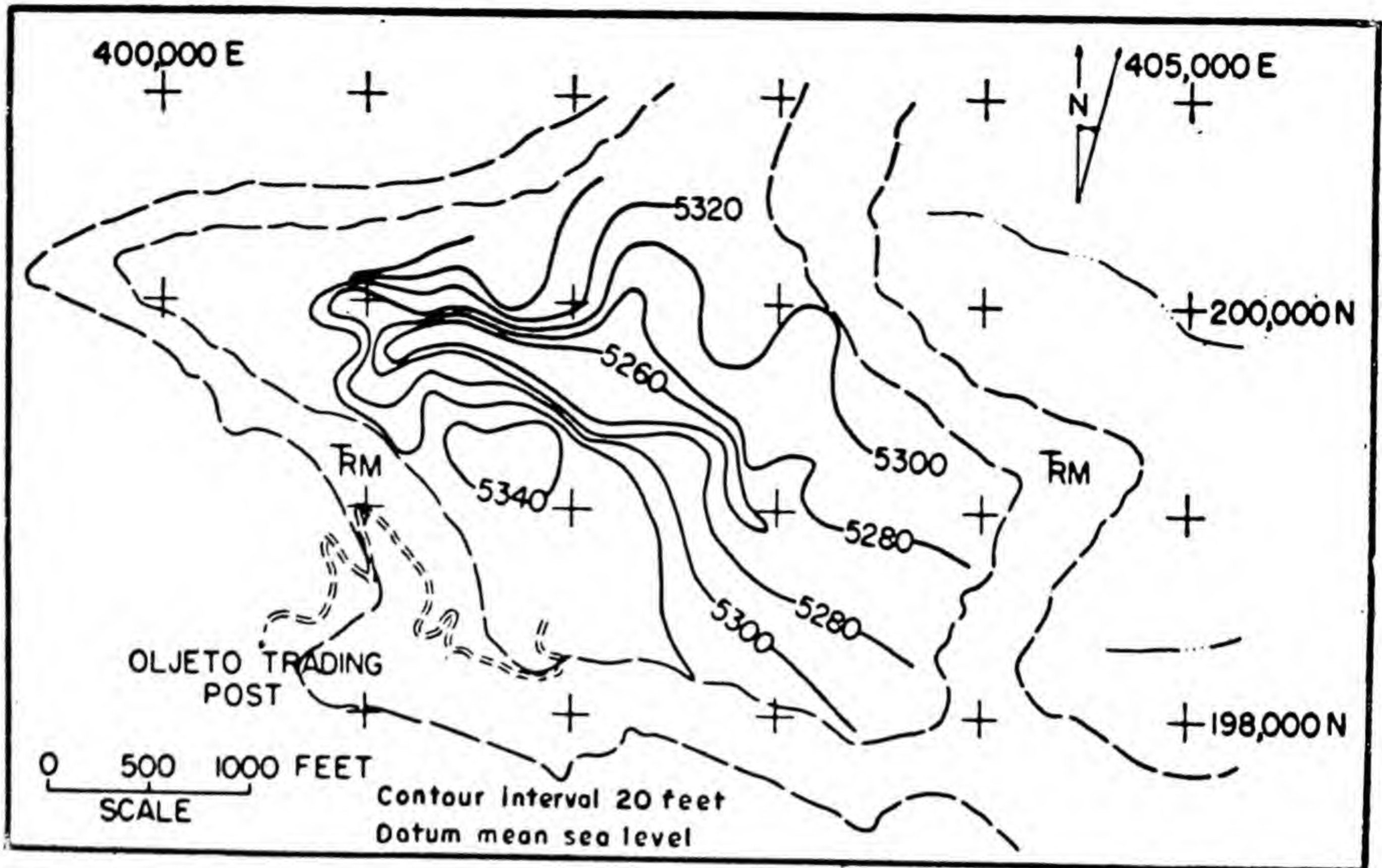


FIG. 12.4. Subsurface contour map of top of Moenkopi formation as determined from seismic data.

response, high paper speed, and variable presuppression control. The equipment is a conventional reflection seismograph modified to permit the recording of higher frequencies, at shorter time intervals after the first energy arrivals.

Shallow-reflection tests were made in three areas representing geologic conditions typical of Morrison and Shinarump uranium deposits. Shallow reflections were recorded in all three test areas, although they were often discontinuous and showed erratic step-outs which made interpretation difficult. More work is planned, using pattern charges and multiple geophones, to improve the character of the reflections. If record quality can be improved, it is possible that the shallow reflection technique will prove a valuable aid to uranium exploration.

#### BOREHOLE GEOPHYSICAL METHODS

**Electric logging.** Although surface electrical-resistivity methods have been successfully used in exploration for relatively shallow Morrison uranium deposits, such methods could not be used where the overburden is thicker than 800 feet.

Experimental electric logging tests were made in 1953 by G. V. Keller and 1954 by R. E. Miller using multiple-electrode equipment capable of recording self-potential logs, single-point resistance logs, 4-inch and 24-inch normal resistivity logs, and 18-inch lateral logs.



The electric logging tests suggested several possibilities that deserve further investigation. The single-point resistance log can furnish an accurate lithologic log that can be used for stratigraphic correlation between drill holes from which there is poor or no core recovery. A combination of a single-point resistance log, a gamma-ray log, and wagon drilling would be a cheap, efficient exploration method. Electric logs, combined with inhole velocity logs, provide an excellent means of evaluating the possibilities of surface geophysical work in any new areas in which the physical properties of the formations are unknown or in doubt. The discovery by G. E. Manger of the possible association of changes of amount and salinity of pore water with uranium mineralization may mean that variations in pore-water saturations, and thus proximity to uranium ore deposits, can be mapped with electric logs.

**Surface-inhole electrical methods.** Tests have also been made of combinations of surface and inhole electrical methods in an attempt to extend the effective radius of drill holes by mapping directional-resistivity trends from these drill holes. Variations in apparent resistivity were measured in a radial pattern around drill holes, employing both surface and inhole electrodes. A modified electric logging unit was used with surface electrode configurations to make the directional-resistivity measurements. A number of different electrode configurations were tested using a 16 cycles-per-second current and recording the potential readings continuously as the inhole electrode moved up the hole.

Lateral-resistivity changes can be mapped with this method, but great care must be taken to avoid false directional-resistivity anomalies due to variable contact resistances between the surface electrodes and the earth. Surface-inhole electrical methods may prove to be of value by effectively increasing the area investigated by a drill hole from a matter of inches to as much as 200 feet.

#### OTHER GEOPHYSICAL METHODS

The electrical properties have been determined for several cores of the Morrison formation obtained by special drilling procedures to preserve the natural water content. These measurements indicate that significant differences exist between the dielectric constants of the mudstones and sandstones of the Morrison, when measured at low frequencies. The measurement of charge-discharge curves may be useful in tracing lithologic variations in the Salt Wash sandstone member of the Morrison formation.

The laboratory measurements on natural state Morrison cores also indicate that radio waves may be useful in investigating lithologic variations in the sandstones of the Morrison. The rate of attenuation of radio waves in mudstones of the Morrison is many times greater than in sandstones of the Morrison, and the sandstones may thus act as dielectric wave guides. It is possible



that measurements of the rates of decay of radio waves initiated within the sandstone may permit mapping of lithologic variations within the sandstone.

The electromagnetic-induction method may also prove applicable to prospecting for uranium deposits. Arid country, with its dry surface layer, is particularly favorable for the electromagnetic-induction method, since a non-conducting surface layer permits greater depth penetration.

### SUMMARY

The U.S. Geological Survey has tested a wide variety of geophysical methods on the Colorado Plateau to determine which could be used to aid in exploration for uranium deposits. The seismic-refraction and the electrical-resistivity methods have proved particularly applicable to uranium exploration. Magnetic and natural potential methods have as yet proved to have no direct application to uranium exploration.

Shallow seismic reflection, electric logging, and surface-inhole electrical methods have been tested, but not enough information has been obtained to determine fully their application to uranium exploration. Induced polarization, radio-frequency, and electromagnetic-induction methods look promising and will be further developed in the near future.

### SELECTED REFERENCES FOR CHAPTER 12

- Barthelmes, A. J., 1946: Application of continuous profiling to refraction shooting. *Geophysics* 11:24-42.
- Black, R. A., 1954: District geophysical studies. In *Geologic Investigations of Radioactive Deposits, Semiannual Progress Report, June 1 to November 30, 1954*. U.S. Atomic Energy Commission TEIR-490:78-85 (Technical Information Service, Oak Ridge, Tennessee).
- Keller, G. V., 1954: The application of electric logging to a mineral exploration program. *Geophysics* 19:631-632.
- Manger, G. E., 1954: Original state core studies. In *Geologic Investigations of Radioactive Deposits, Semiannual Progress Report, June 1 to November 30, 1954*. U.S. Atomic Energy Commission TEIR-490:92-94 (Technical Information Service, Oak Ridge, Tennessee).
- Pakiser, L. C., D. R. Mabey, and R. E. Warrick, 1954: Mapping shallow horizons with reflection seismograph. *Am. Assoc. Petroleum Geologists Bull.* 38:2382-94.
- Wantland, D., and R. D. Casey, 1952: *Field Tests for the United States Atomic Energy Commission on the Use of the Seismic Geophysical Method for Tracing "Buried Channels" in the Monument Valley Area, Arizona*. U.S. Bureau of Reclamation Geology Report G-123.



# *Chapter 13*

---

## GEOPHYSICAL-GEOCHEMICAL PROSPECTING \*

---

---

Geophysical and geochemical exploration methods are based upon determination of variations in some physical or chemical property associated with a mineral deposit. The unique property of radioactive disintegration of thorium and uranium has aided immeasurably in surface prospecting for these metals. However, a thin (two feet or less) rock cover absorbs such radiation, and when the deposit is buried, other geophysical and geochemical techniques must be applied.

Proven aids in the search for radioactive materials are seismic reflection and refraction, continuous interval velocity logging, electromagnetic induction, electrical well logging, surface-resistivity, surface-radiometric, and geochemical determinations of trace elements and associated anions.

Decisions on the kind and sequence of geophysical and geochemical techniques which may be most suitable for a given area are based upon geological, geophysical, and geochemical reconnaissance. To this end and also for interpretational purposes, representative soil, water, or rock samples are analyzed for physical property variations and chemical content.

Inherent variations attributable to topographic, geographic, and climatic or atmospheric effects are considered. Their effects may be evaluated empirically or statistically by means of extensive laboratory and field data.

### FIELD SURVEY DATA

**Southern Black Hills, South Dakota.** Surface-resistivity studies carried out at various locations in the southern Black Hills were initiated to confirm an apparent relation between permeable fracture systems and mineralization and to outline known ore bodies.

Data have been obtained using modified Gish-Rooney equipment designed for use with three current and three potential electrodes and having a variable

\* From Geneva Paper 515, "Geophysical-Geochemical Prospecting for Uranium" by M. E. Denson, Jr., U.S. Atomic Energy Commission.



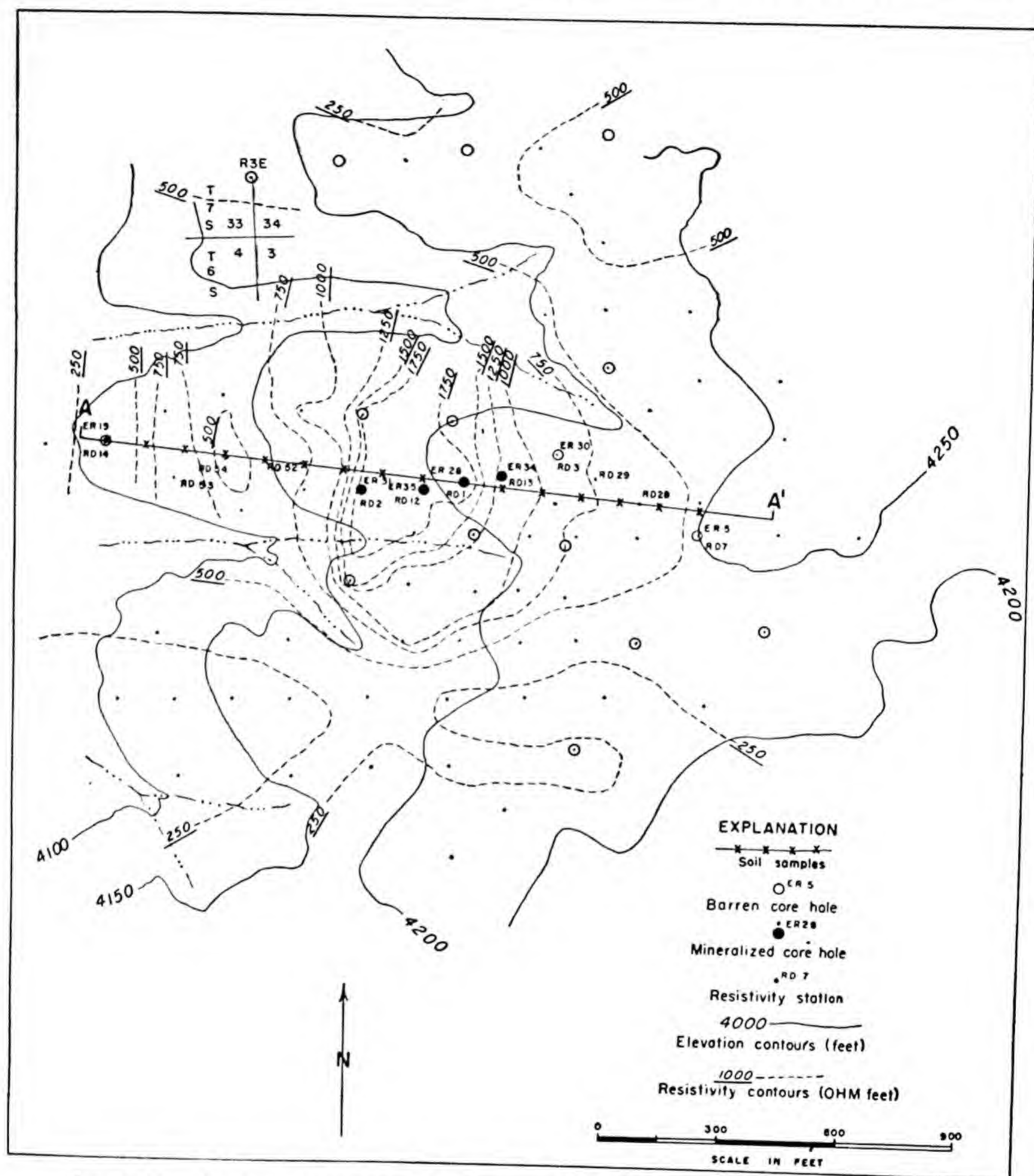


FIG. 13.1. Surface-resistivity data, East Red Canyon, Fall River County, South Dakota.

power supply. One man can complete eight depth profiles per day with this equipment; three men, thirty or forty profiles. Depth profiling ("electrical drilling") was carried out using the four equidistant electrode Wenner arrangement and the five electrode Lee configuration.

Surface-resistivity data obtained from the East Red Canyon area are shown in Figure 13.1. These results, which show apparent resistivity to a depth of 70 feet, clearly indicate that in this case mineralization is associated with



anomalous values of resistivity. Both the ore-bearing horizons and the overlying sediments exhibit resistivity values abnormally high for such thicknesses of clays, mudstones, silts, and sands. Theoretical calculations to determine true resistivity were not made in view of the great number of lateral and vertical changes in stratigraphy.

Electric logs (single electrode, resistance) from the drilled holes along profile AA' (Fig. 13.1), and surface resistivity and geochemical data along the same profile are shown in Figure 13.2. Water leaches of the soil samples were

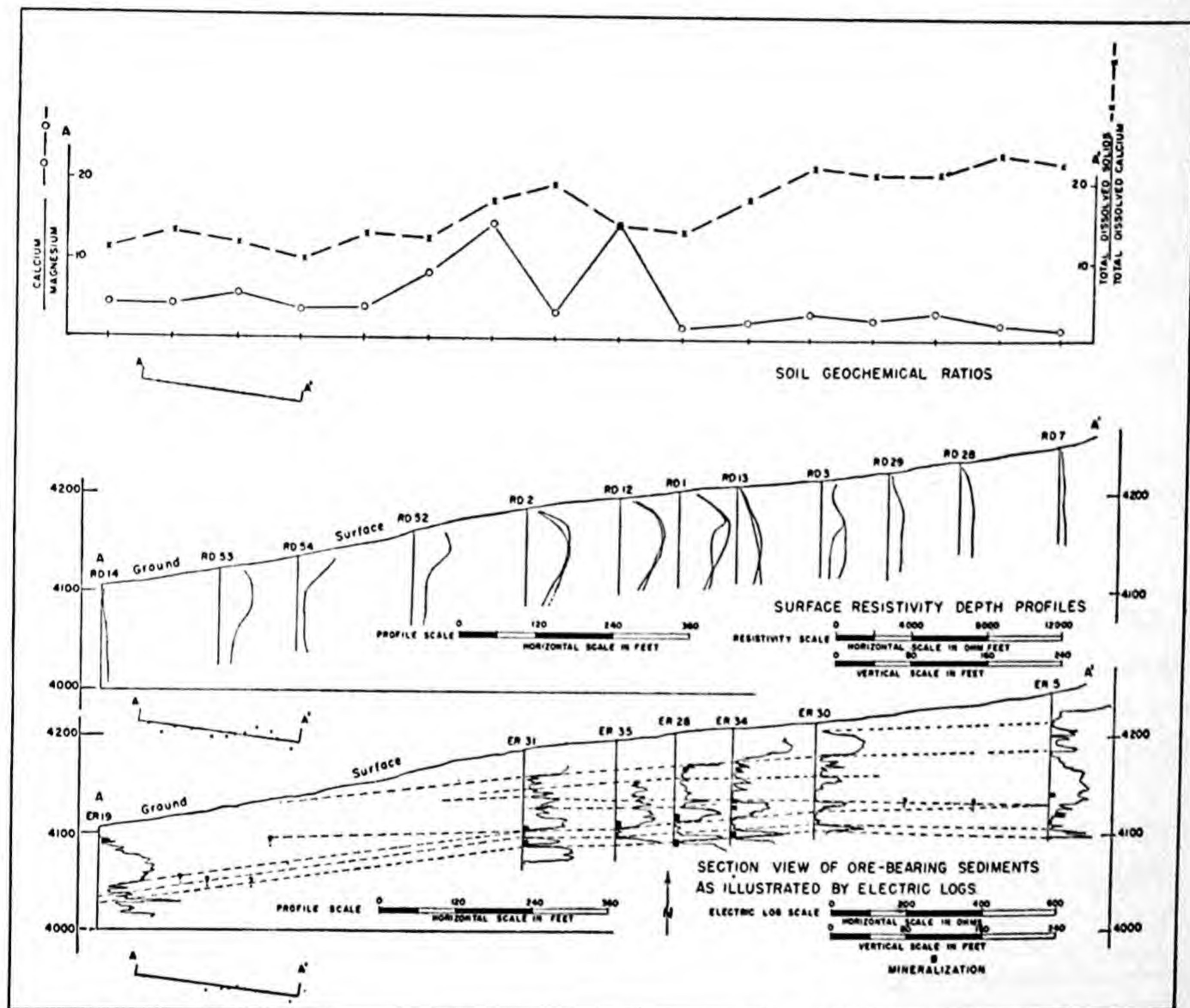


FIG. 13.2. Geophysical-geochemical sections, East Red Canyon, Fall River County, South Dakota.

analyzed for content of Ca, Mg, Na, K,  $\text{HCO}_3$ ,  $\text{CO}_3$ , Cl, pH, conductivity, and total dissolved solids.

These results indicate that at this locality the Ca/Mg ratio appears to be a significant exploration parameter. Displacement of the anomalous values downslope along the topographic surface is evident. When used in conjunction with surface-resistivity surveys, geochemical field determination is economic



and simple. The inhole electric logs demonstrate that the contrasting variations shown in the electrical data obtained from surface measurements are related primarily to variations in sedimentation. Fracture systems may be of significance since different results were obtained (Fig. 13.2) from depth profiles run over the same points but laid out in different directions. Electric logs from Holes 5 and 19 at the ends of the section show a similar type of sedimentary unit which is totally different from the mineralized units which lense in and out between Holes 5 and 19.

Physical-property determinations and petrographic inspection of cores indicate that the major sand unit at Holes 5 and 19 contains minor amounts of silica cement (locally recrystallized) and abundant clay cementing material. Porosity of this main unit is about 28% and permeabilities range from 600 to 900 millidarcies. Preliminary analyses (insufficient in amount for generalization) suggest that the porosities of the sharply bounded sand units in the intervening holes will average 23% or less and will have permeabilities considerably higher than those of Holes 5 and 19. Since the beds lie above the water table and are not water-saturated, infiltration of water from the borehole takes place during logging operations. This precludes quantitative comparison of the departure magnitudes of the electric logs; however, the lower resistance values of the sand units at Holes 28, 30, 31, 34, and 35 denote a high water imbibition and hence a high permeability.

Correlations extending in a north-south direction indicate a local sedimentary trend. This trend could be of a scour-and-fill deltaic depositional pattern or a change of facies such as would occur along a terrestrial shore line. Data presented are believed to indicate a "channel-like" deposit having a hydrologic system different from the bounding strata. Measured electrical conductivities of water from wells in the southern Black Hills aquifers range from 1000 to 3150 micromhos. Measurements on cores indicate that the formation waters of the East Red Canyon mineralized sediments contain very small amounts of dissolved solids and the formation resistivities range from 1400 to 10,000 ohm-cms. Mineralization in this area appears to be controlled by both structural and depositional factors.

Data from the Gould area, southern Black Hills, are shown in Figures 13.3 and 13.4. Soil profiles (Fig. 13.3) were laid out in relation to resistivity patterns and sampled every 50 feet to determine possible useful relations between ore location, resistivity, and soil chemistry. Water leaches of the samples were analyzed for Ca, Mg, Na, K,  $\text{HCO}_3$ ,  $\text{CO}_3$ , Cl, pH, conductivity, and total dissolved solids. No general relations can be stated, but values shown on Figure 13.3 indicate that variations in the ratio of  $\text{HCO}_3$  to water conductivity are higher over non-ore-bearing beds. Ca/Mg values vary in a manner consistent with variations at East Red Canyon, although the values are more erratic, apparently because of topography. Correlation on the cross-



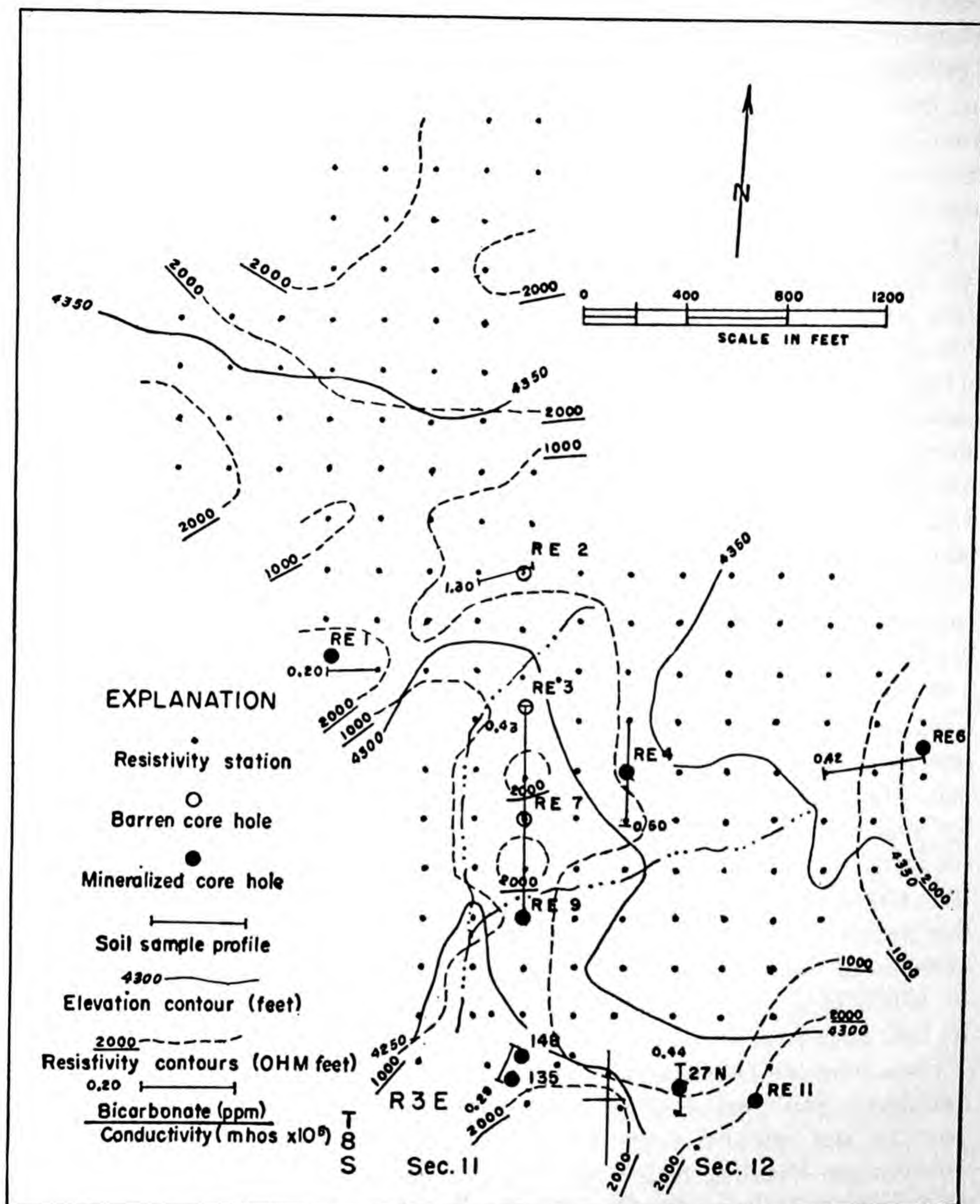


FIG. 13.3. Resistivity and soil chemistry data, Gould area, Fall River County, South Dakota.



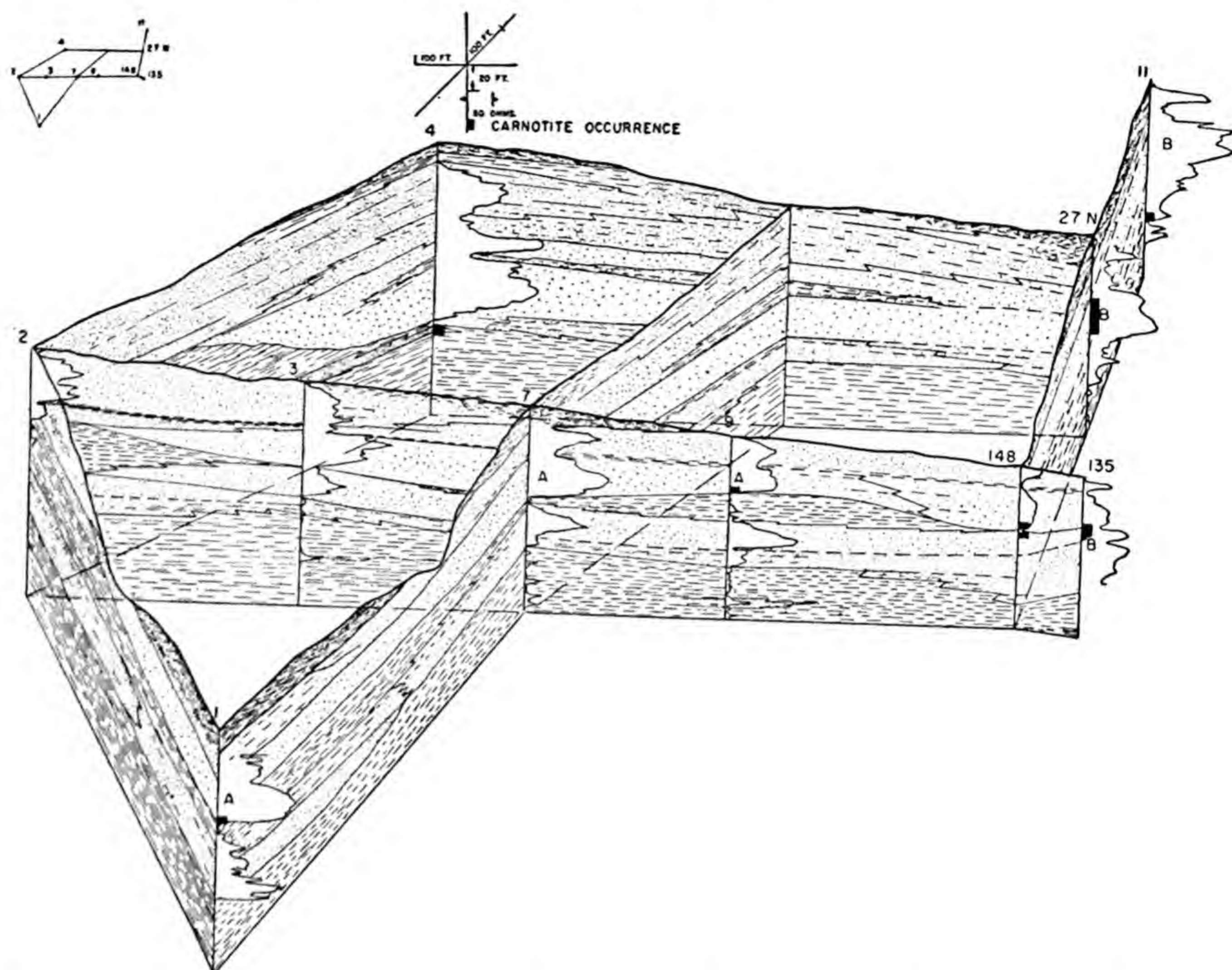


FIG. 13.4. Stratigraphic relations of ore-bearing sediments as illustrated by electric logs, Gould area, Fall River County, South Dakota.

sectional fence diagram (Fig. 13.4) made from single electrode inhole electric logs illustrate the complexity and variability of the stratigraphy in this area. Magnitudes of the electric-log departures are not comparable, since some holes would not hold water without continuous replenishment during logging operations. However, the types of departures at Holes 1, 7, and 9 illustrate scour-and-fill deposition where the high-resistance sandstones (marked A) lie directly over impermeable mudstones of varying thickness. This type of departure contrasts sharply with the upward gradational transitions from mudstones to sandstones (marked B) on logs from Holes 11, 27 N, and 135.

The linear patterns of the surface resistivity data (shown for a depth of 100 feet, Fig. 13.3) are interpreted as dominantly sand-filled scour channels braiding throughout the area. These high-resistivity channel-like areas grade to low-resistivity areas, as at 27 N, 11, and 6, and at these locations the inhole electric logs indicate transitional deposition. Limited analyses indicate that permeabilities in the channel-like units range from 2000 to 5500 millidarcies, while in the transitional units variation ranges from 30 to 2000 millidarcies.



Decreases in permeability are caused by diminishing grain size and increased content of clay-sized cementing material.

The most abundant mineralization occurs at Holes 27 N, 135, and 6 in or near surface-resistivity transitional zones. The slight mineralization at Holes 1 and 9 at the base of the channel-like sand units may suggest that these permeable units have served as conduits for the mineralizing solutions. Variations in surface electrical data, interpreted to indicate changes in permeability between channel and transitional-zone sediments are a useful exploration guide. Although no faulting is evident from the field data, it is reasonable to assume that small scale faulting may have served as one of the controls on mineralization.

**Wind River Basin, Wyoming.** Results of inhole electric-logging studies and surface electrical surveys over the Bull Rush prospect, Gas Hills area, of the Wind River Basin are shown on Figure 13.5. Results from surface electrical depth profiles indicate that the ore body there is centered in low-resistivity sediments. The variations, though clear, are of small magnitude, implying a high degree of water saturation. The concave-shaped low-resistivity pattern on Figure 13.5 (apparent depth 80 feet), which is bounded by higher resistivities, suggests an overlapping transitional sedimentary sequence.

Correlations of the electric logs from open holes along the north-south profile (Fig. 13.5) illustrate the factors controlling the resistivity variations of the surface data. The logs indicate a slightly dipping, transitional sequence of sands and clays. The overlap or gradation of the predominant sands at hole A 9 to predominant sandy clays or mudstones at hole A 13 causes the change from higher to lower resistivity determined on the surface. The slight southern dip of the beds intersecting the topographic nose causes the anomalous pattern to be bow-shaped.

Whether the sediments close to hole A 15 change in dip or in facies is not clear in view of lack of electric logs from the nearby holes, but a change in facies appears reasonable. A small flexure or fault, accompanied by dip changes near hole A 15, would be consistent with data.

Electric logs from this area were obtained using a dry-hole contact logging unit only recently developed. Axial length of the electrode contact (1 inch) is less than one-quarter of the hole diameter, which permits determination and comparison of the resistivities of beds whose thicknesses exceed about 2 feet. For such beds direct proportionality exists between true resistivity and measured resistance between 1 and 1000 ohms. This dry-hole tool has much advantage not only for indicating stratigraphic detail but also for quantitative interpretation of resistivity parameters. Magnitudes of the electrical departure on the logs are comparable. This dry hole unit has been run in holes which had been filled with fluid and logged with conventional single-point equipment.



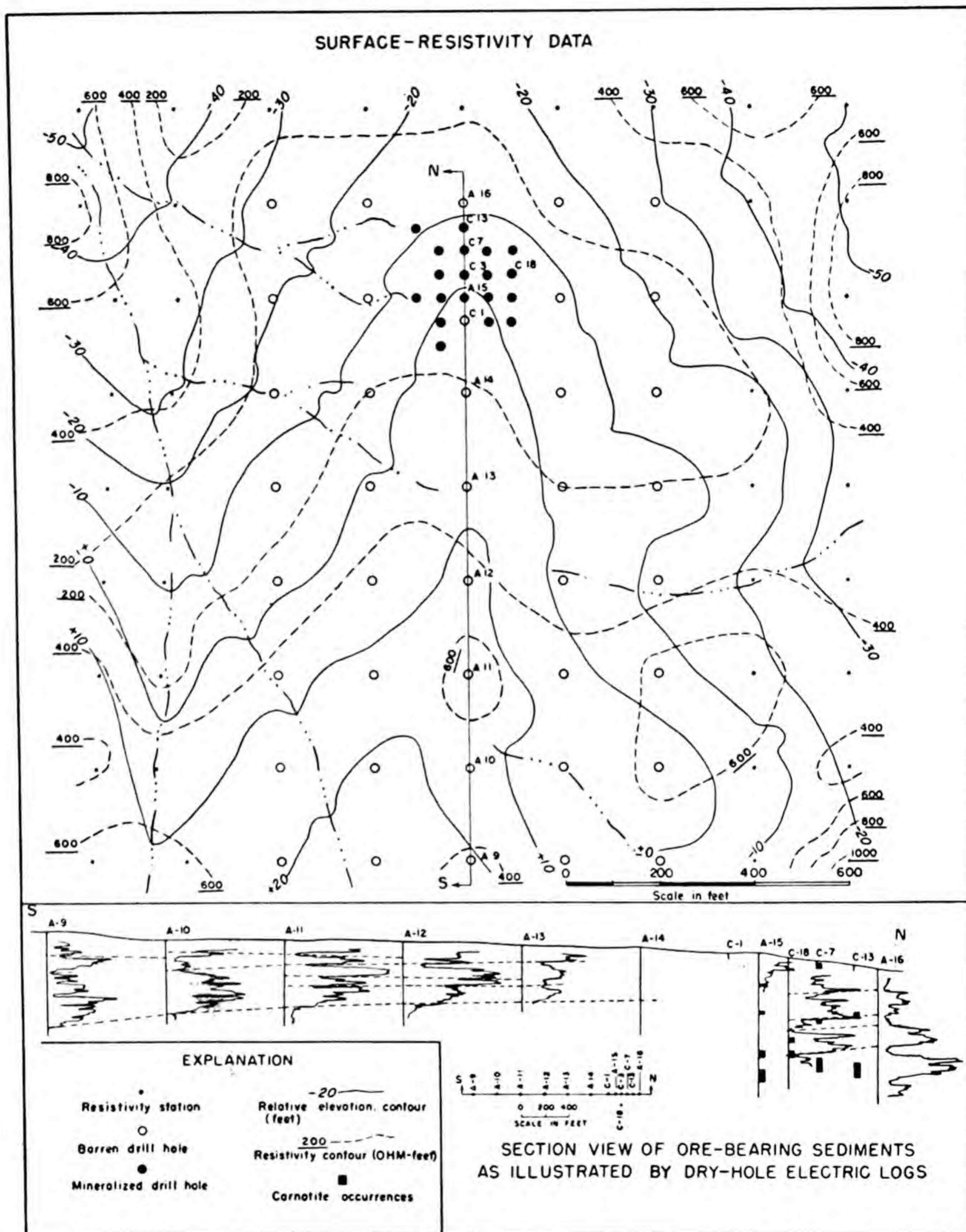


FIG. 13.5. Bull Rush prospect data, Wind River Basin, Fremont County, Wyoming.



The dry-hole logs are repeatable and compare closely with the wet-hole logs except that more detail and definition is obtained with the dry-hole unit.

### DISCUSSION OF DATA

Surface and inhole resistivity indicate that uranium mineralization is accompanied by variations in the sediments which are detectable by electrical means. No significant variation in resistivity of a mineralized sand is known to be attributable to the uranium mineralization. However, it may be instructive to note that in the three sets of data shown, the first two (southern Black Hills) display predominantly high resistivity values; the mineralization is dominantly carnotite. At the Wind River Bull Rush prospect the resistivities are low and the chief minerals are the calcium-uranium-phosphate, autunite, and the uraniferous calcite, liebigite. It is interesting to speculate that the differences in the sediments as indicated by resistance measurements reflect a set of conditions which relates to the type of mineralization.

Geochemical analyses of soils over deposits 80 feet or more below the surface may or may not show readily recognizable relation to the location of ore, depending upon the stratigraphy involved. However, these analyses do relate to the directly underlying sediment and under certain conditions afford very useful data. When used in conjunction with geophysical surveys, geochemistry becomes more practical and economic.

### RECONNAISSANCE DATA

**Colorado Front Range.** Small-magnitude anomalies of extended pattern are screened by carrying out geochemical analyses on soil, water, and rock samples collected in relation to the anomalies.

Low-level radiometric data are obtained by a high-sensitivity detecting unit with a sensitivity of about 120 cps per MR per hour, mounted on a jeep station wagon. Data are recorded on a strip chart synchronized to run at 3 inches per mile. Traverses may be spaced from  $\frac{1}{2}$  to 1 mile apart.

Variations in the recorded values of counts per second are transferred from the strip chart to a base map and contoured. Corrections are applied for cosmic effect and topographic features. Cosmic variations are determined by retraversing and by base-line measurements. Topographic corrections are applied empirically. Uniform radioactive content of the exposed surface area is assumed except where outcrops or measurements indicate otherwise. Surface geology exerts a marked influence, particularly where carbonaceous shales crop out.

Recorded anomalies are checked by carrying out geochemical analyses for uranium, thorium, and potassium on specially picked samples. Scattered



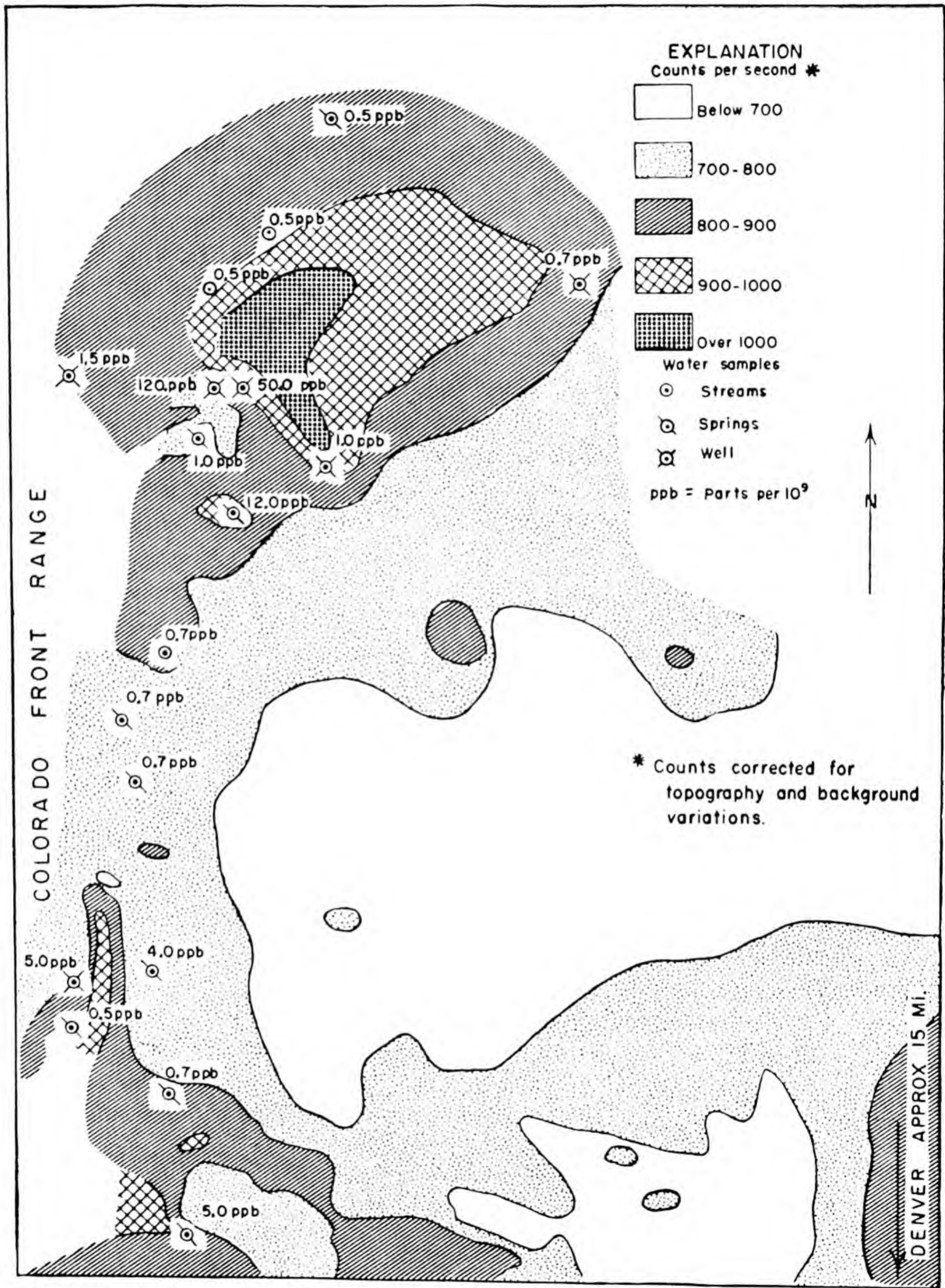


FIG. 13.6. Radiometric-geochemical reconnaissance data, Colorado Front Range, Colorado. Scale 1:72,000.



anomalies of small extent can usually be ascribed to alluvial variations unless they maintain abnormal patterns of distribution. Drainage ways are most frequently characterized by an increase in count, which is not generally an effect of topography.

Figure 13.6 is an example of combined radiometric-geochemical reconnaissance data from an area where no previous exploration of this type has been carried out. Traverses were run arbitrarily about one mile apart over the greater part of the area. Anomalous areas were checked by running traverses at quarter-mile spacing, and shorter where possible. The area to the north and east consists of flat-lying sediments partially covered by alluvial material of varying thickness.

Water samples were collected close to the three anomalous areas shown. Variation in uranium content of these waters ranges from 0.5 to 120 parts per billion ( $10^9$ ). The correlation of high uranium content in waters and areas of slight increases in radioactivity is clear. Uranium contents of 120 to 50 parts per billion in formation waters are believed to indicate destruction of a uranium deposit.

#### EXPERIMENTAL DATA

In order to obtain adequate depth control for shallow resistivity and seismic data, evaluation of high-resolution seismic reflection equipment is in process. Continuous velocity logging equipment was used in conjunction with the high-resolution equipment to obtain detailed velocity-depth relations. This provides information on the thicknesses and acoustic impedance contrasts necessary to obtain high-frequency reflections (up to 500 cps) as well as to determine possible correlations between resistivity and velocity. Further, the limitations to be expected using seismic refraction and reflection equipment can be determined. Results and correlations obtained using continuous interval velocity logging can be shown.\*

The degree of correlations between velocity, resistivity, self-potential (as determined from inhole logs) and porosity (as determined from core measurements) is significant. In the silica and carbonate-cemented sediments, increases in velocity relate to decreases in porosity. Determination of such relations in ore-bearing areas is of importance and interest in exploration.

\* See C. B. Vogel, "Seismic velocity logging methods," *Geophysics* 27:586-97 (1952).



# *Chapter 14*

---

## GEOCHEMICAL PROSPECTING \*

---

Geochemistry is a broad, borderland field of science concerned with the relative and absolute abundance of the elements in the earth and the laws covering their distribution, dispersion, and concentration. Most scientific prospecting, whether geological or geophysical, uses geochemical facts and laws to help interpret observations in an effort to hasten and cheapen the discovery of mineral deposits. By general consent, however, the term "geochemical prospecting" refers to the search for concealed mineral deposits through the detection and proper interpretation of the subtle yet diagnostic chemical patterns that may be present in naturally occurring materials in the vicinity of an ore body. The patterns most commonly sought are variations in the content of certain diagnostic minor elements in readily accessible material—variations either in the ore metals or in associated indicator elements. All good prospecting techniques fulfill three requirements: they must be adequate, relatively cheap, and rapid. Geochemical prospecting has been very successful in attaining these requirements.

Geochemical techniques were first used some twenty years ago by Scandinavian and Russian geologists to locate certain types of ore deposits, but it was not until after World War II that the use of geochemical prospecting became widespread. Geochemical techniques have had their greatest success in the search for deposits of copper, lead, and zinc, but many of the techniques and principles established are of value in the search for deposits of uranium and thorium.

\* Except for the last paragraph, this chapter is from Geneva Paper 508, "The Use of Geochemical Techniques and Methods in Prospecting for Uranium" by T. S. Lovering, F. C. Canney, H. W. Lakin, and F. N. Ward of the U.S. Geological Survey. The last paragraph is from Paper 764, "Methods of Prospecting for Uranium and Thorium" by C. F. Davidson and S. H. U. Bowie of the Geological Survey of Great Britain.

Selected references are listed alphabetically at the end of the chapter.



## GEOCHEMICAL ANOMALIES

A significant departure from the average abundance or background value of an element in materials where the distribution has not been disturbed by mineralization is called a "geochemical anomaly." Values less than background would be called a "negative anomaly," whereas those above background constitute a "positive anomaly" or simply "an anomaly." Although background values can vary widely as a result of natural processes, in most barren materials the distribution of elements has a log normal distribution as recently suggested by Ahrens, and there is a figure near which most of the values lie, with higher and lower figures in rapidly diminishing frequency on either side. The threshold of significance is commonly about twice the value of the peak for the background, and the importance of a geochemical anomaly is best brought out by using a geometric ratio for isograms; when representing geochemical results on a map the isograms would represent 2, 4, 8, 16, and 32 times the background value of an element, rather than 2, 3, 4, 5, and 6 times the background figure. Our present knowledge concerning the mechanisms by which anomalies form is so scanty that there is considerable risk in any attempt to correlate the contrast and size of an anomaly with the tenor of the underlying mineralized body. Nevertheless, an area surrounded by several such isograms would seem more worthy of immediate attention than an area with but one.

Geochemical anomalies are of two general types: Primary anomalies are genetically related directly or indirectly to ore-depositing processes and may be regional or local in extent. Secondary anomalies are those formed at the surface of the earth by agents of weathering, erosion, surficial transportation, or biological activity. Evidence is accumulating that suggests that certain broad regions having a very marked increase in the background value of an element may be considered geochemical or metallogenetic provinces. Intrusive rocks in some uranium-rich regions show a much higher background of uranium than do similar rocks in regions lacking uranium deposits. In establishing a regional anomaly, it is necessary to compare the metal content within specific rock types, for there may be a far greater variation between different rock types within a metallogenetic province than between the metal content of a specific rock type within and outside of the province.

Metallogenetic provinces usually have a background several times that of the average for a given rock type, and within the province there may be local concentrations that are still broader than an individual ore deposit—district anomalies, which may run several times the background of the metallogenetic province. Many uraninite-bearing veins have been found in the early Tertiary mineral belt of the Colorado Front Range, and both pre-Cambrian and Tertiary



intrusive rocks have a much higher uranium content than the average of their types. In addition, there are regional variations within a given variety of igneous rocks that show the uranium content is severalfold greater in districts containing uraninite veins than elsewhere.

The background that is characteristic of different rocks, such as granite in contrast to gabbro, may vary severalfold, or even by an order of magnitude. The anomalies that reflect this kind of variation in the original composition of the rock yield primary anomalies of little value in the search for individual ore deposits and must be distinguished from other anomalies caused by the impregnation of rocks by ore-bearing fluids. These other primary anomalies may be more limited in extent, but are of the utmost importance and include chiefly wall-rock and leakage halos. Wall-rock halos probably form during the emplacement of the ore by the impregnation of a sheath of the surrounding wall rock with those associated elements that are relatively mobile. Leakage halos are similar in nature, but follow the channelways along which the ore-forming fluids moved.

Each area studied is unique and requires its own adaptation of geochemical techniques, but certain principles can be used in deciding on the combination of methods most suitable. The study of primary anomalies must be based on a knowledge of the geology and mineralogy of the mineral deposits. It is also important to realize that a primary leakage halo may be either on the outlet side of a blind ore body or on the inlet side of an eroded ore body, and furthermore, that an anomaly at the surface may not be vertically over the ore. Leakage of solutions that moved upward at an angle would result in an anomaly that was offset from a vertical position over the blind ore body sought—a "displaced anomaly." Pyritic halos that are so commonly associated with uranium ore deposits, whether of the sandstone type or of the cross-cutting vein variety, may be regarded as the outer ring of a target area; the problem of the prospector is to find the bull's-eye which may be at the side, the center, or in between. Similar dispersion of niobium around some thorium deposits has been observed, and it is known that minor amounts of vanadium, copper, lead, zinc, and other metals are locally associated with certain uranium deposits. Some sandstone-type uranium deposits have only a small primary anomaly of uranium itself but may be prospected geochemically by a search for the more extensive primary anomalies of these associated metals.

Anomalies of surficial origin—secondary anomalies—result from the weathering of rocks and ores, from biogeochemical processes, and from dispersion of ore minerals and metals through transportation by glacial ice, by slide and creep of colluvium, and by moving ground water and surface water. The shape and size of the secondary anomaly depends on the climate and topography, and on the mobility of the various elements present under the conditions of weathering that obtain where the deposits crop out or underlie the soil. Mobility,



as the term is generally used, is a measure of the tendency of an element to dissolve in the zone of weathering and to migrate from the original deposit. The dispersion pattern reflects the chemical equilibria characteristic of the local environment, the abundance of the element in the disintegrating rock, and the movement of earth material from one environment to another. Dispersion patterns that are mapped at the surface are usually regarded as two-dimensional features, but the fact that dispersion has three-dimensional geometry is important when interpreting secondary anomalies and is vital to success when considering primary anomalies.

Dispersion patterns are commonly classified as halos, fans, and trains, depending upon the characteristic shape of the pattern and its relation to the locus of primary concentration. A halo encloses the source of the material; a fan is a pattern spreading outward in a fan-shaped mass from a source at the apex of the fan; a train is a linear dispersion pattern commonly trending downgrade away from the deposit in secondary anomalies and downgrade toward the deposit in a primary anomaly.

In areas where pyritic halos have weathered to form limonite, the edge of the limonitic area will commonly be enriched in manganese and zinc and the weathered pyritic area will commonly be impoverished in these metals. This distribution gives rise to a negative anomaly in the weathered pyritic area and to an encircling positive anomaly where the metals have been concentrated by precipitation from supergene solutions. These anomalies obviously do not reflect the presence of an ore deposit but only decreased acidity in the surface solutions and surrounding rocks lacking high sulfur, and illustrate the necessity of proper geochemical interpretation of anomalies and the importance of distinguishing between anomalies related to ore-forming processes and those that are not.

In many areas the analysis of soils for uranium or other ore metal gives a fairly reliable and consistent indication of ore that is concealed beneath. Biogeochemical processes tend to concentrate certain elements at the surface even though the source of the element may be at a depth of many meters. The accumulation of zinc, uranium, vanadium, selenium, sulfur, and other elements in plant tissues has long been known, and convincing evidence has been found that these elements tend to enrich the surface layers as the organic material in which they were concentrated is decomposed through biogeochemical agencies at the surface. In areas where there is an appreciable zone of plant litter, samples of the underlying soil must be studied with the possibility in mind that the minor-element content has been pumped to the surface through the root systems of plants. It is quite possible, however, to establish target areas on the basis of geochemical anomalies produced in this way. In semiarid regions where little or no plant debris accumulates, analysis of the vegetation itself for uranium or other ore metal may provide the information



necessary to disclose the presence of a hidden ore body tapped by the root systems of the plants.

Under favorable conditions metals in small amounts are also introduced into transported soil which covers a truncated ore deposit. Unlike the anomalies caused by concentration in decaying vegetation, these superimposed halos show a concentration gradient increasing downward and probably reflect diffusion or capillary movement in moist regolith overlying an oxidizing ore body. Such anomalies may be the geochemical analogue of geophysical self-potential anomalies related to decomposing sulfide ores. The more mobile elements, such as sulfur, zinc, cobalt, uranium, and—under alkaline conditions—molybdenum, are the elements most likely to be found in superimposed or diffusion halos. These are also the metals most likely to be leached from the residual soil or gossan over an ore body. The metals sought in residual material over an ore body would be those of low mobility, such as thorium, lead, copper, vanadium, niobium, selenium, and arsenic, although there is usually a perceptible rise in the concentration of the more mobile elements associated with the ore in the general vicinity of the ore deposits as contrasted with the barren rocks surrounding it.

The search for geochemical anomalies in transported material is most commonly directed toward finding a dispersion train or fan that may lead the prospector back to the bedrock source of detrital ore minerals. Such a search is merely a modern extension of the age-old techniques of searching out lodes by panning gravels for gold or other heavy minerals and of following the increasing concentration of the detrital minerals upstream to their source.

In using geochemical methods to search for uranium, both the direct search where uranium itself is sought and the indirect method where primary or secondary halos of associated elements are the targets have considerable promise. Although geochemical methods have not been widely used to detect uranium because of the ease with which radiometric anomalies can be found by air-borne, truck-borne and hand-carried instruments, the importance of a radiometric high must always be ascertained by chemical analyses. In areas subject to radioactive fallout from atomic fission devices, contamination may make radiometric techniques nearly useless without constant chemical check. A simple, sensitive, and inexpensive field method of analysis for uranium (reported later in this paper) allows quick evaluation of such anomalies and makes it possible to discriminate between anomalies caused by uranium and those related to thorium or to daughter products. This chemical method is also of value in testing nonradioactive materials for recently deposited uranium or in areas where there is a substantial cover over uranium bodies and, as a consequence, the radioactivity of the ore bodies is not appreciable at the surface. In the surface soil horizons of such localities a very slight



concentration that diminishes downward may be highly significant and suggests the probability of biogeochemical concentration from depth.

It is always desirable to make preliminary orientation surveys in geochemical investigations so that the geochemical problems can be evaluated before embarking on a full-scale program. The use of geochemical techniques is especially advantageous when searching for ore bodies that have primary or secondary halos much larger than the ore deposits themselves; the size of such halos can be determined by studies near known ore deposits. Geochemical surveys may fail needlessly even when the analytical work is satisfactory, if the type of anomaly sought does not exist or if the samples were taken in the wrong places, in the wrong materials, or with the wrong spacing. Preliminary work should establish the proper procedure to be followed.

For successful geochemical work there are five problems that must be considered: (1) the element to be sought and the establishment of valid background values, (2) the material best suited for sampling, (3) the geometric pattern for sampling best suited to the geology, (4) the maximum permissible spacing of the samples necessary to reveal anomalies, and (5) the most effective analytical procedure. The answers to these problems depend on the kind, size, contrast, and homogeneity of the anomaly, and on the chemical facilities available. Since most geochemical anomalies result from movement of solutions, soil, or rock, it is apparent that the climate, the topography, and the size and shape of the source of the material are the most important factors determining the geometry of a sample pattern. After some information has been obtained from preliminary orientation studies about the expected general size and shape of the dispersion pattern sought, the geometry and spacing of the samples are chosen so as to assure that at least two, and preferably more, samples will fall within the zone of an anomaly. Where the size and shape of the mineral deposit are unknown, it is common practice to run traverses parallel and at right angles to topographic features, such as ridge crests and valleys. Anomalies developed by diffusion into barren material above ore are usually of small extent and may require sample spacings of 3 to 20 meters. In glacial till, a spacing of 100 to as much as 500 meters may be effective in locating ore-bearing detritus in dispersion trains or fans.

#### ANALYTICAL METHODS FOR GEOCHEMICAL EXPLORATION

The analytical methods used in geochemical prospecting are methods of trace analysis. Trace analysis is the process of determining exceedingly small amounts of the desired constituent in the presence of large amounts of other elements, many of which may interfere seriously in the reactions involved. When a method of trace analysis applicable to these materials is available, the development of a suitable field method becomes one of engineering and



adaptation; that is, volumes and weights are decreased, apparatus and operations are modified. Separations are held to a minimum by the use of complexing agents and changes in valence, but unavoidable separations are made by using immiscible solvents, usually with a relatively small volume, to concentrate the element being measured. For example, the molybdenum method described later is an adaptation of a method that originally required a high-temperature furnace, platinumware, large separatory funnels, and a spectrophotometer.

Similarly, spectrographic methods and equipment that find use in geochemical prospecting are engineered and adopted to use under field conditions. In contrast to the usual techniques of quantitative spectrography, which involve measurements of intensity ratios of line pairs on a photographic plate or film, semiquantitative methods are used, and the concentration of an element is determined by visually comparing the blackness of a line of an element with the blackness of the same line emitted from standards having known amounts of that element. Standard and unknown samples should be as nearly alike as possible in chemical composition and physical characteristics and must be treated alike in the procedure used to produce the spectra. It is expected that spectrographic methods will find their maximum usefulness in large-scale programs where each sample must be analyzed for several elements in an early survey to help select the most diagnostic group of elements.

Specific applications of paper chromatography and colorimetry to methods useful in prospecting for uranium and for possible associated elements are made below. Each method is fast, simple, and moderately accurate, and each is designed to give positive tests for background material in large areas of the United States and to give results within 30% to 50% of the correct value for materials containing anomalous amounts of a given element.

Many comparisons of the results obtained by these methods with those obtained by recognized procedures show that they have adequate accuracy for use in geochemical prospecting for uranium and associated elements.

Elements most commonly associated with uranium deposits in the United States include vanadium, molybdenum, selenium, niobium, copper, and cobalt; the methods used to determine uranium and these indicator elements by the U.S. Geological Survey are outlined in the following pages. With one exception all the methods described below have been used to delineate areas of mineralization in various parts of the United States; with the exception of selenium all the methods have been used by technicians in the field and in the analytical laboratory to analyze 30 to 80 samples in an eight-hour day.

#### DETERMINATION OF ELEMENTS

**Uranium.** This method permits the determination of 4 to 400 ppm of uranium in a soil or sedimentary rock without modification. It is unsatisfactory



for the determination of uranium occurring as a constituent of a refractory mineral. The method described below is a modification of a paper chromatographic procedure for use in geochemical prospecting described by Hunt, North, and Wells. A 1-gm sample is digested for 1 hour in a boiling water bath with 2 ml of 1 + 3 nitric acid saturated with aluminum nitrate. A 0.01-ml aliquot of the supernatant solution is placed on a Whatman CRL/1 filter paper and dried in a desiccator over calcium chloride for 8 minutes at ambient temperatures of 60° to 90°F and for 5 minutes when temperatures exceed 90°F. The lower end of the dry paper is immersed in a developing solution (30 ml ethyl acetate, 3.5 ml concentrated nitric acid, and 10 ml of water contained in a 600-ml beaker) until the solution has risen about 8 cm in the paper. Then the paper is removed from the developing solution, dried, and sprayed with a 5% aqueous solution of potassium ferrocyanide, and the resulting stain of the brown-colored uranium complex is compared with standards similarly prepared.

This procedure differs from that of Hunt, North, and Wells by the addition of a relatively large amount of aluminum nitrate to the sample solution to facilitate the determination of uranium in phosphatic materials. In addition, the residual salts on the filter paper after evaporation are essentially constant, and differences resulting from varying solubility of the sample are nullified.

**Vanadium.** Without any modification the vanadium method given here is useful on soils or rocks containing from 0.03% to 2.0% vanadium. It is particularly applicable to oxidized materials and suffers from no interferences except that of niobium.

This wet chemical method for determining small amounts of vanadium in soils or rocks is based on a hitherto unused reaction of vanadium (III) with thiocyanate in acid medium. A 0.1-gm sample is heated with 1 ml of 9 molar sulfuric acid, and after cooling, is treated successively with 4 ml of 10% aqueous sodium citrate, 2 ml of 2% disodium ethylenediamine-tetraacetic acid, 3 ml of 15% stannous chloride in concentrated hydrochloric acid, and 2 ml of 20% aqueous potassium thiocyanate. The yellow-colored complex is extracted into 1 ml of ethyl ether, and the intensity is compared with that obtained from standard solutions to determine the vanadium content.

**Molybdenum.** The field method for molybdenum can be applied to soils and rocks containing from about 1 to 32 ppm of molybdenum, and in this concentration range the precision of repeat determinations is within a few parts per million.

This method for determining traces of molybdenum in soils and rocks is based on the reaction of molybdenum (V) with thiocyanate in dilute hydrochloric acid and subsequent extraction of the complex into isopropyl ether.

A 0.1-gm sample is fused with 0.5 gm of a 1 + 1 mixture of sodium carbonate



and potassium nitrate, in a borosilicate glass test tube, and the fused mass is extracted with 4 ml of hot water. A 1-ml filtered aliquot of the aqueous extract is neutralized with molar hydrochloric acid and treated with 0.5 ml of 10% aqueous potassium nitrate and 0.2 gm solid sodium tartrate. The volume is adjusted to 5 ml with water and treated successively with 0.5 ml concentrated hydrochloric acid, 0.3 ml of 5% aqueous potassium thiocyanate, and 0.5 ml of 10% stannous chloride in 2 molar hydrochloric acid. The amber-colored molybdenum complex is extracted into 0.3 ml of isopropyl ether to concentrate the colored complex and increase the over-all sensitivity of the method. The colored ether layer obtained from a sample is compared with that obtained from standard solutions to determine the molybdenum content of the sample.

**Selenium.** This method is useful for the semiquantitative determination of selenium in soils, rocks, and vegetation containing from 2 to 100 ppm of selenium. It is not suitable for field use. The method is a microchemical adaptation of the well-known distillation procedure of Hillebrand *et al.*, combined with Franke's confined spot method of estimation. A 1.0-gm sample of the soil, rock, or vegetation is evaporated slowly with 10 ml of nitric acid containing 10 mg each of mercuric oxide and ammonium metavanadate, until 2 ml remains. The mixture is fumed with 10 ml of concentrated sulfuric acid and then centrifuged at 1500 rpm for 10 minutes, after which the supernatant liquid is decanted into a 125-ml distillation flask. Ten milliliters of concentrated hydrobromic acid and a few drops of bromine are added, and 8 to 10 ml is distilled into a beaker containing 2 ml of water and a few drops of bromine. The distillate is reduced with sulfur dioxide and 1 ml of a saturated aqueous hydroxylamine hydrochloride solution, digested on a steam bath for 20 minutes, and set aside for 12 hours. The precipitated selenium is collected on a paper disc covered with a barium sulfate mat by filtering the distillate through the disc fixed between two sections of glass pipe held firmly together with a suitable coupling. The pink selenium spot is compared with standard spots prepared similarly.

**Copper.** The colorimetric method described here is designed for the estimation of copper in soils and rocks containing 20 to 4000 ppm. The method is based on the reaction of copper in an acidic solution with diphenylthiocarbazone (dithizone) to form a pink copper dithizonate soluble in carbon tetrachloride. A 0.1-gm sample of soil or rock is digested for 1 hour on a boiling water bath with 3 ml of 1 + 3 nitric acid and then diluted to 10 ml with metal-free water. A suitable aliquot is transferred to a test tube containing 1 ml of 10% sodium citrate solution and 2 drops of thymol blue solution. The pH is adjusted to 2.5 with 1 N hydrochloric acid. To this solution 2.5 ml of 0.001% dithizone solution in carbon tetrachloride is added, the mixture is shaken vigorously for 2 minutes, and the resulting color of the organic phase is compared with that of standards similarly prepared.



**Cobalt.** The cobalt method is applicable to soils and rocks containing from 10 to 500 ppm of cobalt. It is based on the reaction of cobalt with 2-nitroso-1-naphthol to form a pink-colored complex soluble in carbon tetrachloride. A 0.1-gm sample is fused with 0.5 gm of potassium pyrosulfate, and the cool melt is extracted with 10 ml 0.5 molar hydrochloric acid. A 2-ml aliquot is treated with 1 ml of 10% sodium citrate and 4 ml of 2% aqueous disodium hydrogen phosphate dodecahydrate. The pH is adjusted to 6.5; 3 ml of 0.01% aqueous 2-nitroso-1-naphthol and 1 ml of carbon tetrachloride are added. The pink-colored cobalt complex is extracted into the organic layer, which is separated and shaken with 10 ml of 0.05% aqueous potassium cyanide to decompose the nickel and copper complexes.

The intensity or shade of pink is a measure of the cobalt present, and the comparison of the color produced by a sample with that produced by a cobalt standard provides a means of measuring the cobalt content of the sample.

**Niobium.** The method given below can be applied to materials containing from 20 to 2000 ppm of niobium. It is based on the reaction of niobium (V) with thiocyanate in hydrochloric acid and subsequent extraction of the niobium complex into ether. A 0.2-gm sample is fused with 4 gm of potassium pyrosulfate and extracted with 10 ml of 1 molar aqueous tartaric acid. A 1-ml filtered aliquot is treated with 5 ml of 9 molar hydrochloric acid, which is also 1 molar in tartaric acid. To the cool solution (20° to 25°C) 5 ml of 20% ammonium thiocyanate and 5 ml of ethyl ether are added. After shaking, the ether phase is separated and treated successively with small portions of 10% stannous chloride in 2 molar hydrochloric acid to remove iron, titanium, and other reducible metals whose lower valences are insoluble in ether. The yellow-colored ether phase is diluted with an equal volume of acetone to stabilize the solution and inhibit side reactions. Niobium is determined by comparing the intensity of the yellow color of the ether solution obtained from a sample with that obtained from a standard. The niobium can also be determined by measuring the absorbance of the yellow-colored ether solution at 385 millimicrons and referring to a previously established standard curve.

#### APPLICATION TO URANIUM PROSPECTING \*

The ready migration of uranium in solution on weathering of primary ore suggests that geochemical techniques, involving quantitative chemical analysis for the metal in soils, alluvium, vegetation and surface waters, may be of value in searching for new uranium ore bodies. In prospecting for uranium, however, quantitative chemical studies of soils and alluvium have seldom been undertaken, owing to the ease with which even a low tenor of the radio-

\* Geneva Conference Paper 764.



active elements may be detected by radiometry. But where such analytical examination is being made for other metals, tests for uranium might usefully be incorporated. A rapid method for such work, utilizing paper chromatography, has recently been developed.\* Chemicobotanical techniques involving the analysis of plant ash have also been studied, but seem likely to be useful only in the exploration for extensions of known ore bodies in subdesert regions where there is a thick overburden and plants are deep-rooted. No direct ecological aids to uranium prospecting are known, but locally geobotanical studies can be of indirect assistance: in Colorado, for example, bushes of *Astragalus* are dwarfed where rooted in soils rich in the selenium that commonly accompanies the uranium ore;† and in the Congo-Rhodesian copperbelt certain plants which are commonly found in soils overlying copper-cobalt ores direct attention to mineralization in which uranium may be present.

## SELECTED REFERENCES FOR CHAPTER 14

- Ahrens, L. H., 1954: The lognormal distribution of the elements. *Geochimica et cosmochimica acta* 5:49-73.
- Almond, H., 1953: Determination of traces of cobalt in soils. *Anal. Chem.* 25:166-67.
- Franke, K. W., R. Burris, and R. S. Hutton, 1936: A new colorimetric procedure adapted to selenium determination. *Ind. & Eng. Chem., Anal. Ed.* 8:435.
- Hillebrand, W. F., G. E. F. Lundell, M. S. Bright, and J. I. Hoffman, 1953: *Applied Inorganic Analysis*, 2d ed. New York, John Wiley & Sons, Inc.
- Hunt, E. C., A. A. North, and R. A. Wells, 1955: The application of paper chromatographic methods of analysis to geochemical prospecting. *The Analyst* 80:172-194.
- Reichen, L. E., and F. N. Ward, 1951: *Field Method for the Determination of Molybdenum in Plants*. U.S. Geological Survey, Circular 124.
- Ward, F. N., 1951: Determination of molybdenum in soils and rocks. *Anal. Chem.* 23:788-791.

\* See Selected References, Hunt, *et al.*

† See Chapter 15.



# Chapter 15

---

## BOTANICAL PROSPECTING \*

---

Botanical methods of prospecting are dependent upon the absorption and accumulation of metals and associated elements by plants growing over metaliferous deposits. Two methods of botanical or biogeochemical prospecting have been developed and used by the U.S. Geological Survey to locate uranium deposits on the Colorado Plateau, which includes parts of Colorado, New Mexico, Utah, and Arizona. One method of botanical prospecting currently used is based upon the uranium content of plants; another is based upon the distribution of indicator plants—those that are dependent either directly or indirectly upon the presence of abnormal amounts of uranium and associated elements.

During the past five years, nearly 10,000 samples have been analyzed for uranium, and distribution studies of indicator plants have been made along 80 kilometers of outcrop. A positive correlation has been shown between botanically favorable ground and major ore deposits, and preliminary results indicate that ore may be found at depths to 25 meters by botanical methods of prospecting.

### PROSPECTING BY TREE ANALYSIS

Prospecting by tree analysis is based on the uranium content of trees growing in the area to be prospected. Uranium occurs in all plants in small but measurable amounts. Plant ash normally contains 0.2 to 1.0 part per million uranium. The uranium content of plants rooted in ore, however, may range from 1 to 100 ppm uranium. Therefore the uranium content of plants rooted in ore or within the chemical halo of the ore body may be used as an indication of mineralized ground.

The uranium content of vegetation varies for many reasons, a fact which

\* From Geneva Paper 509, "Botanical Methods of Prospecting for Uranium" by H. L. Cannon, F. J. Kleinhampl (including work by H. F. Froelich and P. F. Narten) of the U.S. Geological Survey.

Selected references are listed alphabetically at the end of the chapter.



should be understood and evaluated before a project of plant analysis is undertaken. The uranium content of trees and herbaceous plants varies slightly with the seasons and the amount of rainfall, but in an area being prospected by day-to-day sampling, this small variation can be discounted. A large part of the uranium absorbed by the plant root is precipitated within the root cells. A lesser amount is transported to the leaves and branches and is in direct proportion to the total uranium absorbed by the roots, so that the presence or absence of mineralized ground may be inferred from leaf or twig analyses. Of importance in prospecting is the variation in uranium content from one side of the tree to another. As the roots of one side of the tree are directly connected to a particular set of branches, the uranium content of the branches may vary depending upon the position of the mineralized ground. It is important, then, to sample a tree on all sides to obtain a representative sample.

Some plant species absorb much more uranium than others. The mechanism by which plants absorb uranium is a matter not of ion transport in a water solution, but of ion exchange. Plant families differ in regard to the amounts of the various ions absorbed because they have different and characteristic buffer systems and resulting variations in cell sap pH. Plot studies indicate that those plants that readily absorb large amounts of sodium, sulfur, selenium, and calcium but small amounts of potassium will also absorb uranium readily. These plants generally have a cell sap pH of less than 5.2. For this reason, conifers and desert shrubs of the rose family that have these characteristics and are common in uranium districts of the Colorado Plateau can be used successfully in sampling programs.

The amount of uranium absorbed by plants is dependent also upon the percentage of water-soluble uranium in the vicinity of the plant roots. The amount of water-soluble uranium present is due in part to the interaction of uranium with other ions present in unusual amounts and does not necessarily reflect the total amount of uranium present. For instance, the percentage of water-soluble uranium in the soil is increased when gypsum, selenium, or lime is added. The addition of carnotite increases the solubility of sulfur and selenium. The latter relationship is important in the localization of sulfur- and selenium-bearing indicator plants. The described changes in solubility of uranium take place under oxidizing conditions, and important differences in the relative absorption of uranium by deep-rooted trees and shrubs have been noted only in areas of oxidizing ore.

The depth to which ore can be detected by plant analysis depends upon the root habits of the species sampled and upon the availability of water. In semiarid country, shrubs and trees commonly have root systems 15 to 25 meters in length. In many uranium districts of the Colorado Plateau, the ore-bearing rock is an aquifer. The roots of junipers, piñons, and desert shrubs penetrate long distances through cracks and crevices connecting with the



water-bearing zone and act as phreatophytes or ground-water plants. Mineralized areas of a coal bed on La Ventana Mesa, New Mexico, were outlined effectively by analysis of piñon and juniper whose roots penetrated a 25-meter sandstone capping the mesa. It is probable, however, that plant analysis is not generally effective in prospecting at depths of more than 20 meters.

In prospecting by the plant-analysis method, a preliminary study must first be made of the geologic relations. This should include observations on the extent, depth, and inclination of the ore-bearing strata, the size and habits of the ore bodies, the probable grade of the ore, the presence or absence of a chemical halo in the surrounding barren rock, and the relation of the ore-bearing bed to the water table and the plant roots. Botanical studies should be made of the growth habits of species available for sampling. Preliminary samples should be collected on both mineralized and barren ground and then analyzed to determine the amount of uranium absorbed by trees in the area under study. Finally, from this geological and botanical information, the sampling medium, the sampling pattern, and sampling interval may be determined.

Several coniferous species have a wide range on the Colorado Plateau, have deep roots, and absorb about the same amounts of uranium. These species, listed in Table 15.1, have been used as the sampling medium on several projects.

TABLE 15.1. TREES USED IN SAMPLING ON THE COLORADO PLATEAU

<i>Tree</i>	<i>Altitude (ft)</i>
<i>Pinus ponderosa</i> Doug. (Ponderosa pine)	7000 to 9000
<i>Pseudotsuga taxifolia</i> Britt (Douglas fir)	
<i>Abies concolor</i> Lindl. (White fir)	
<i>Pinus edulis</i> Engelm. (Piñon)	6000 to 7000
<i>Juniperus scopulorum</i> Sarg. (Rocky Mountain juniper)	
<i>Juniperus utahensis</i> Sarg. (Utah juniper)	4000 to 6000
<i>Juniperus monosperma</i> Engelm. (oneseed juniper)	

Samples of the last year's growth of needles or branch tips collected from the entire periphery of the tree have given the most consistent results.

In areas where the ore-bearing bed occurs in a broad flat bench with a uniform vegetative cover, systematic tree sampling on a grid pattern may be used. Favorable areas may be found by drawing isograms on the uranium values. In areas where the ore-bearing bed crops out in sharp cliffs, line traverses with particular emphasis on close-spaced samples collected on talus-covered areas may prove to be the best sample pattern.

The distance between sampled trees depends in part upon the objective of the project. For rapid reconnaissance, an initial spacing of 75 meters is usually adequate, and in anomalous areas later fill-in samples with 15-meter spacing



may be desirable. A shorter interval of 5 to 10 meters is useful for sampling across talus-covered rim or cliff outcrops.

**Analytical methods.** A fluorimetric method of analysis is used by the Geological Survey for the determination of uranium in plant ash; the method has been described by Grimaldi and others. A portable fluorimeter, powered by batteries, has been designed for field use, and a chromatographic field test for uranium in soils and in plant ash has also been used in Survey laboratories. A method of analyzing the radioactivity of plant ash by alpha count has been developed at the University of Arizona and has been described in a recent paper by Anderson and Kurtz.

A pint container of fresh plant material is collected for fluorimetric analysis under present laboratory procedure. The precision to be expected from the method is 0.5 ppm uranium in the range from 0.3 to 5.0 ppm uranium. The chromatographic method requires much less sample, but is not as accurate in the low ranges as the fluorimetric method.

**Interpretation of results.** Although the amount of uranium absorbed by plants rooted in ore varies slightly with the type of ore and the species of plant sampled, contents above 1 ppm uranium in the ash are considered to indicate favorable and possibly mineralized ground in many areas sampled on the Colorado Plateau. This figure was arrived at empirically from early plant analysis studies and from a statistical analysis of 2000 tree samples. Trees rooted in barren ground were found to average 0.3 ppm uranium in the ash; trees rooted in mineralized ground averaged 1.5 ppm uranium.

Statistical study verifies the conclusions of other workers that a sampling program should be restricted to one kind of tree. However, when it is necessary to use more than one species of tree, special factors relating the different species to one another could be employed. These factors would be obtained by relating the statistical measures of the assay data of each population to the other populations used. The results thus obtained would define more exactly anomalously high values and make the results obtained from the different species comparable.

#### PROSPECTING BY INDICATOR PLANTS

A plant may be used as an indicator plant in prospecting for metalliferous deposits if its distribution is affected by the availability of chemical constituents present in the ore. The plants used in prospecting for a particular type of deposit may not all be controlled by the same factor. They are usually common rather than unusual plants. Indicator plants for uraniferous sandstone deposits are controlled not only by the presence of unusual amounts of selenium and sulfur but by an increased availability of these elements in water-soluble form and by the increased availability of the major plant nu-



trients, calcium and phosphorus. Selenium and sulfur were found by plot experiments to be more readily absorbed by plants in the presence of carnotite, and uranium to be more readily absorbed in the presence of selenium and sulfur. The availability of calcium and phosphorus was also increased in the plots to which carnotite has been added. In addition, each indicator plant, depending upon the specific metabolic processes inherent in the species, reacted differently to the excess materials available for absorption. These experiments explain many irregularities in plant distribution noted in the field.

A correlation between the distribution of selenium-indicator plants and carnotite deposits of the Morrison formation was first noted by O. A. Beath in 1943, in conjunction with toxicity studies of range land. The U.S. Geological Survey has since established the use of selenium-indicator plants in prospecting for uranium. In general the plants are perennials with long tap roots; roots of *Astragalus* have been traced to a depth of more than 10 meters in mine workings. Under favorable conditions the use of *Astragalus* has led to the discovery of ore bodies 25 meters below the surface. *Astragalus* and other seleniferous genera have distinct distribution patterns depending upon the amount of selenium in the ore and the amount required by the plant. Preliminary studies are mandatory in advance of prospecting in each new area to determine the species best correlated in distribution with mineralized ground.

*Astragalus pattersoni* A. Gray, belonging to the vetch group is the most useful indicator plant on the Colorado Plateau. The plant requires large amounts of selenium and commonly absorbs several thousand ppm selenium from uranium ores. Plot experiments suggest that the presence of carnotite increases the absorption of selenium by this plant many times.

The following species of *Astragalus* are also useful in some areas of the Plateau:

- Astragalus preussi* A. Gray
- Astragalus thompsonae* S. Wats
- Astragalus confertiflorus* A. Gray
- Astragalus bisulcatus* (Hook) A. Gray
- Astragalus lonchocarpus* Torr
- Astragalus dodgeanus* M. E. Jones

Other selenium-indicator genera that require only small amounts of selenium may act as indicators of uranium ore containing less than 2 ppm selenium. These include:

- Aster venustus* M. E. Jones (Woody aster)
- Grindelia* spp. (Gumweed)
- Oryzopsis hymenoides* (R. and S.) Rick (Indian ricegrass).
- Stanleya* spp. (Prince's plume).



Many uranium ores contain sulfides that commonly form gypsum upon weathering. Sulfur- and calcium-absorbing ephemeral plants occur where this gypsum moves upwards into surface soil within reach of shallow plant roots. Sulfur- and calcium-absorbing ephemerals include:

- Allium* spp. (Wild onion)
- Calochortus* spp. (Sego lily)
- Zigadenus* spp. (Camas lily)
- Sisymbrium* spp. (Tumble mustard)
- Lepidium* spp. (pepperweed)
- Eriogonium inflatum* Torr. (Desert trumpet)
- Cryptantha* spp. (Cryptanth)
- Oenothera caespitosa* Nutt. (Tufted evening primrose)
- Oenothera albicaulis* Pursh. (White-stemmed evening primrose)
- Stipa comata* Trin. and Rupr. (Needle-and-thread)
- Elymus salina* Jones (Salina wild rye)
- Aplopappus armeriodes* A. Gray (Goldenweed)
- Senecio longilobus* Benth (Threadleaf groundsel)
- Mentzelia multiflora* Nutt. A. Gray (Desert blazingstar)

It should be emphasized that the plants used as indicators in prospecting may be common roadside weeds in other areas of the country. The chemical elements that control their distribution around metalliferous deposits, particularly selenium and sulfur, are present in all rocks, but their concentration varies greatly in different stratigraphic units. The plants may be useful prospecting tools where the difference in chemical composition between barren parts of the ore-bearing bed and the ore itself is enough to affect the flora.

The effectiveness of indicator plants as a guide to uranium deposits depends largely on the depth to mineralized ground and the availability of selenium and sulfur to the plant roots. In turn, species of indicator plants vary in their root habits and in their capacity to absorb selenate and sulfate ions. Much depends on whether the elements in question are present only at ground-water level or have migrated to the soil surface along fractures or through permeable beds.

The distribution of indicator plants can be plotted directly on maps or photos as a result of field observation without the necessity of collection or analysis. Indicator-plant prospecting is rapid and inexpensive and therefore is preferred over prospecting by plant analysis if conditions permit.

Preliminary studies are necessary in each area to be prospected to determine what plants in this particular area correlate most closely with the extent of the mineralized ground. An initial mapping of several dozen plants may eventually resolve itself into a final mapping of two or three species which may be plotted by symbol on maps or on air photos. From a study of the



resulting plant maps, favorable areas may be delineated for detailed geologic evaluation and possibly for exploration.

For the most effective use of plant distribution maps, a careful study should also be made of the sedimentary features, direction of ground-water movement, joint fracture patterns, folding, and other topographic and geologic features. Many drill holes have been inauspiciously placed in a futile attempt to test plant information without due regard to the probable origin and migration of water-soluble ions.

#### RESULTS OF BOTANICAL PROSPECTING ON THE COLORADO PLATEAU

Botanical prospecting studies have been made in advance of exploration in five districts of the Colorado Plateau. Of these only one area has subsequently been completely explored by diamond drilling. Preliminary drilling programs have been started in two other districts. Results indicate that prospecting by indicator plants is advantageous in areas of the Plateau where uranium ores average about 0.01% selenium and are at an average depth of not more than 15 meters beneath the ground surface. Prospecting by tree analysis is advantageous in areas where the tree cover is continuous and the ores are not more than 25 meters in depth. It is also important that the ore-bearing formation be an aquifer.

Prospecting by indicator plants has been tested in the Yellow Cat area, Grand County, Utah, where plants were mapped over an area of 10 square kilometers and nearly 2000 holes were subsequently drilled. The ore in this area occurs in the Salt Wash sandstone member of the Morrison formation and contains vanadium, uranium, selenium, and sulfur. The distribution patterns of nine species of plants were originally mapped on a scale of 1:6000. Final maps were compiled on the distribution of four species.

An analysis has been made of the relation of plant distribution patterns to results of the first 1000 holes drilled in the area. Holes ranged in depth from 3 to 85 meters. A total of 26 holes were in ore in the first 1000 holes drilled, and all 26 penetrated ore at a relatively shallow depth. Twenty-one of the holes containing ore were in areas of indicator plants. Five ore bodies out of a total of ten were found entirely on plant data. Indicator plants were found to reflect mineralized ground to an average depth of 22 meters, but proved to be a more dependable ore guide when ore is at depths of less than 15 meters. Ten per cent of the barren holes, 50% of the mineralized holes, and 80% of the ore holes were drilled in areas of indicator plants.

A comparison of the effectiveness of indicator species in the area showed that the selenium-indicators *Astragalus pattersoni* and *A. preussi* are the most reliable indicators of mineralized ground and that the sulfur plants *Allium*



*acuminatum* and *Eriogonum inflatum* may act as competent indicators where the ore lies at depths of no more than 10 meters.

Several ore bodies have also been found in the Grants district, New Mexico, as a result of indicator-plant prospecting. A project of prospecting by plant analysis was conducted during 1952-54 on the ore-bearing Jurassic Todilto limestone. Results of the program show that botanically defined anomalies delimit areas that are favorable for the discovery of uranium deposits, and preliminary drilling information indicates that botanical anomalies correlate with mineralized ground. On Elk Ridge, Utah, botanical sampling programs have defined areas where physical exploration for uranium may be warranted, as a study of the outcrop near botanically defined anomalies shows a positive correlation with geologically favorable criteria such as secondary copper and iron staining, carbonaceous trash, pyrite, and channel fillings.

#### SELECTED REFERENCES FOR CHAPTER 15

- Anderson, R. Y., and E. B. Kurtz, Jr., 1955: Biogeochemical reconnaissance of the Annie Laurie uranium prospect, Santa Cruz County, Arizona. *Econ. Geol.* 50:227-232.
- Beath, O. A., 1943: Toxic vegetation growing on the Salt Wash sandstone member of the Morrison formation. *J. Botany* 30: 698-707.
- Cannon, H. L., 1952: The effect of uranium-vanadium deposits on the vegetation of the Colorado Plateau. *Am. J. Sci.* 250:735-770.
- 1953: *Geobotanical Reconnaissance near Grants, New Mexico*. U.S. Geological Survey Circular 264.
- Grimaldi, F. S., I. May, and M. H. Fletcher, 1952: *U.S. Geological Survey Fluorimetric Methods of Uranium Analysis*. U.S. Geological Survey Circular 199.
- Grimaldi, F. S., I. May, M. H. Fletcher, and Jane Titcomb, 1954: *Collected Papers on Methods of Analysis for Uranium and Thorium*, U.S. Geological Survey Bulletin 1006.



# Chapter 16

---

## HYDROGEOCHEMICAL PROSPECTING \*

---

In prospecting for underground deposits of uranium considerable help may be derived from a detailed examination of radioactive materials brought up by water or gases. Further aid may also be obtained from the study of the isotopic composition of nonradioactive elements.

Among the radioactive elements which are of importance in hydrogeochemical prospecting are (1) uranium, (2) radium, (3) radon, (4) krypton-85, (5) xenon-133, and (6) tritium. The first three are, of course, members of the uranium family. Krypton-85 and xenon-133 are produced by fission (both spontaneous and neutron-induced) of uranium, and tritium originates primarily with meteoric water. Among the properties of nonradioactive elements, of special significance are changes in the isotopic abundance of deuterium, oxygen, nitrogen, helium, and argon.

Water sources may be classified according to the content of radium and radon as follows:

- I. Radium present ( $> 5 \mu\mu\text{curies/liter}$ ) †  
High radon content ( $> 10^3 \mu\mu\text{curies/liter}$ )
- II. Little or no radium present ( $< 5 \mu\mu\text{curies/liter}$ )  
Radon present ( $> 10^2 \mu\mu\text{curies/liter}$ )
- III. Little or no radium ( $< 5 \mu\mu\text{curies/liter}$ ) or radon  
( $< 10^2 \mu\mu\text{curies/liter}$ ) present

These results depend not only on the size and nature of the deposits but also on the nature of any intervening structures, the motion of the underground

\* The first section of this chapter is from Paper 773, "Measurements on Natural Water Sources as Aid in Prospecting for Underground Deposits of Uranium" by S. Amiel and L. Winsberg of the Israel Atomic Energy Commission and the Weizmann Institute of Science, Israel.

Selected references are listed at the end of the chapter.

† 1 micro-microcurie =  $1 \mu\mu\text{curie} = 10^{-12} \text{ curie} = 2.22 \text{ disintegrations per minute}$ . For radium (with a half-life of 1620 years) the activity of  $10^{-12} \text{ gm}$  is  $1 \mu\mu\text{curie}$ . For radon (half-life 3.82 days) the activity of  $6.3 \times 10^{-18} \text{ gm}$  is  $1 \mu\mu\text{curie}$ . [Ed.]



water, and the chemical and nuclear properties of the two indicators. In order for radium to be present, the water must have passed through the deposit (Type I). This need not be the case for radon since it is a chemically inert gas and can therefore be transported by other gases or move by means of its own diffusion.

Because the half-life of radon is short relative to most geological processes, water of Type II probably passes close to a deposit. On the other hand, lack of radon does not necessarily mean the absence of a deposit in the vicinity, since the intervening structures may not be sufficiently permeable to permit the passage of radon in a time of the order of its half-life. Thus Type III may either conform to this situation or be due to an absence of an appreciable deposit.

A value for the minimum size of a deposit associated with a well being pumped continuously or with a flowing spring can be calculated from the radon content and the rate of flow. We can take as a typical example a spring containing  $10^4 \mu\mu\text{c}$  Rn per liter with a flow of 100 liters per second, i.e., having an output of one  $\mu\text{c}$  Rn per second. This corresponds to 1.3 tons of uranium under equilibrium conditions.

The actual size of the deposit is certain to be much greater than this figure. It would, therefore, be useful to have other evidence to bear on this point. Among the various decay products of uranium, the rare gases are most useful for this purpose. These are helium and radon from alpha decay and krypton-85 and xenon-133 from spontaneous fission of uranium-238 and from neutron-induced fission of uranium-235. Because of the difficulty of decontaminating from radon, the content of xenon-133 is not being measured in this laboratory.

Let us again consider a spring flowing at the rate of 100 liters per second but containing 0.01 cc helium per liter, i.e., having an output of 1 cc per second. To produce this quantity of helium under equilibrium conditions, the deposit must contain  $2.5 \times 10^8$  tons of uranium. The extreme magnitude of this figure suggests that most of the helium content of such a spring originates from a trapped helium source.

In principle the krypton-85 content provides a better indication to the size of the deposit than radon because of its relatively long half-life and its smaller atomic weight. We have so far achieved a sensitivity of 0.1 disintegration per minute per liter of gas, or per 50 liters of water at ordinary temperature, since the dissolved gas is primarily air or nitrogen. For a flow of 100 liters per second, this corresponds to the order of  $10^6$  tons of uranium. For a smaller water flow the minimum size of deposit which can be detected is proportionally smaller.

Other information may throw light on the nature and location of the deposits. The alpha particles from the decay of uranium can react with the constituents of the deposit, forming neutrons. Reactions induced by neutrons and alpha particles can cause changes in the isotopic ratios of the rare gases. For example



very low values of the  $\text{He}^3/\text{He}^4$  ratio have been found in rich uranium ores. Changes in the abundances of the argon isotopes by way of secondary reactions depend on the presence of chlorine. Low values for the  $\text{N}^{14}/\text{N}^{15}$  ratio have been found in gases occluded in uranium and thorium minerals. This field of investigation is just developing and it is, therefore, not yet possible to evaluate the usefulness of this type of measurement.

Besides all the preceding information the following additional data can be brought to bear on the location of the deposit: the salt content, temperature, seasonal variation of flow, the presence or absence of dissolved oxygen, tritium content, and the isotopic abundance of deuterium and oxygen. These are clues as to whether the water is of recent meteoric origin, whether the water originates from a great depth, or whether mixing has occurred.

Together with knowledge of the geology of the region, the information gained from a detailed investigation of natural water sources should prove helpful in planning a drilling program.

#### GROUND AND SURFACE WATER SAMPLING IN THE UNITED STATES \*

Hydrogeochemical methods of finding and estimating the economic possibilities of uranium deposits, based upon differences in the uranium content of natural waters, were developed and tested under known conditions in uranium-mining areas in 1952 after earlier work had shown promise. These methods are now sensitive and accurate, as the result of continuing refinement of field and laboratory techniques and standardization for different types of environment in which uranium may occur. Their validity has been proved by data from more than 700 water samples from uraniferous localities in the United States. Results agree closely with those of radiometric and geologic methods, but hydrogeochemical methods, because of the deep penetration by water underground, also can be used in some places where other methods fail.

Comparative studies were made with both borosilicate glass and polyethylene bottles (in various sizes) with and without stabilization by hydrochloric or nitric acid. Hydrochloric acid is used in the standard procedure adopted. The few samples that contained sediment were decanted into clean bottles after standing for a short time. Filtering was avoided. Uranium is determined fluorimetrically in laboratories of the U.S. Geological Survey, and as yet there is no field method for the determination of the small amounts of uranium present in most samples.

This paper summarizes some of the results of more than 700 uranium determinations, 170 semiquantitative spectrographic analyses in which 60 ele-

\* From Geneva Conference Paper 506, "Geochemical Prospecting for Uranium by Sampling Ground and Surface Waters" by P. F. Fix, U.S. Geological Survey.



ments were sought, and 230 chemical analyses for major and some minor elements in water samples representing most of the western United States and southeastern states. In addition to these data, 2400 uranium determinations were made on water samples collected by other members of the U.S. Geological Survey.

**Factors affecting hydrogeochemical exploration.** Uranium deposits seldom occur under simple geochemical conditions, hence a hydrogeochemical search for them involves appraisal of the net relative effect of such complex variables as the mineralogy of the deposit; the oxidation of associated sulfide minerals; the geology of the area; the pH, chemical composition, oxidation-reduction potential, temperature, and content of colloids, clays, and organic matter of the waters; the season; the climate; the relationship between stream underflow and surface flow; and the circulation pattern of the ground water. With due regard for these variables, the uranium content of the water serves as a rough index of the uranium concentration in the geologic materials hydrologically tributary to the sample site.

Hydrogeochemical methods of finding and appraising uranium deposits are based upon the fact that weathering and erosion produce a secondary dispersion aura of uranium dissolved in ground and surface waters. The aura ordinarily resembles the deposit in ground plan, although it is much more extensive, except in the direction of the hydraulic downgradient, where it is sharply asymmetric owing to the ease with which most waters can dissolve and carry uranium.

Most of the uranium is carried away in ground water and appears ultimately at the land surface in streams. Ordinarily, little is carried away directly in surface water, but the amount may be large where easily soluble uranium minerals in dry-season efflorescences or uraniferous dusts from mining operations or haulage are swept away by storm waters.

The effect upon the uranium content of ground waters by snow melt or storm waters ordinarily is one of proportional dilution, but where ground water at low stage is reduced to virtual stagnancy by a dry season or drought, the sudden influx from the surface above may steepen the hydraulic gradient and flush the ground water from crevices where it has been enriched by long soaking contact with uranium minerals. The sudden addition of such water to other ground water that has been circulating may result temporarily in a large increase in the net uranium content of the whole immediate body of ground water, until dilution by the surface water can take effect.

Ground water enters streams as underflow and hillside springs. Thus, streams are used to detect uranium deposits by hydrogeochemical methods because of the great distances at which dispersion auras can be detected in streams. The sampling pattern resembles that of gold panning. Water samples are collected from streams above their confluences, as well as at any inter-



mediate points that may be promising geologically. Samples are taken far enough above confluences to be certain that the sample site is not affected by underflow from the other fork of the stream. Samples are never taken immediately below confluences, as the chemical blending of two streams requires distances ranging from several hundred meters in small streams to several kilometers or more in rivers.

A single aura, even from a small deposit, ordinarily is easily detected and evaluated downgradient at distances of hundreds of meters in ground water, and at least 20 kilometers in streams. The auras of closely spaced deposits blend into a single composite aura. The greater the number of deposits per unit area and the greater the solubility of the uranium minerals, the shorter is the distance at which an individual aura can be distinguished from its neighbors.

Under favorable conditions, the dense aura of a large uranium deposit, or a major composite aura, is easily detectable quantitatively downgradient as far away as several kilometers in ground water, and probably at least a hundred kilometers in streams. Work in progress on the Dolores River in the semiarid Colorado Plateau suggests that the effect of a major aura may decrease only 50% in a distance of about 80 kilometers downstream, where dilution by large tributaries is a minor factor.

A typical example, taken from the Boulder batholith in Montana, includes detection of an individual aura and tracing its effect through a neighboring composite aura from a uranium mine and several prospects. The climate in the region is semiarid, and the samples were taken after a dry summer when both surface and ground-water inflows to the streams were at a minimum. Mine water from a sulfide base-metal vein with some radioactive black mineral contains 11 ppb \* uranium at the portal. Uranium in this mine was discovered by the writer with the following suite of samples, after an earlier sample at the 3-kilometer point had disclosed the presence of uranium in the drainage basin. The effect downstream from the mine is shown in Table 16.1.

Influx of ground water in the first 9 kilometers is very small, and probably none contains more than 2.7 ppb U. The changes in uranium content of water in the 18 kilometers are in almost exact proportion to the volume and uranium content of incoming streams and well-controlled estimates of ground water influx. The effect of the first aura downstream decreases about 50% in the first 6 kilometers, when the additive effect of the second small tributary is considered. The following effects are shown successively: the additive effect of the tributary from the first unit of the composite aura, the effect of the creek upon the uranium content of the master creek, and the net effect of all at the lower end of the composite aura. At that point, the effect of the first aura can still be detected when relative volume of water is considered. Its effect has been detected several kilometers farther downstream.

\* Ppb = parts per billion = parts per  $10^3$  million =  $10^{-3}$  ppm. [Ed.]



TABLE 16.1

Distance (km)	U (ppb = $10^{-3}$ ppm)	Source of Water Sample
0	11	Mine water at portal.
0	0.9	Creek above mine portal.
1	4.3	Creek after blending with mine water.
1.5	0.8	Small tributary.
2.3	2.7	Small tributary.
3	4.3	Creek after blending with tributaries.
4.7	1.0	Large tributary.
6	2.3	Creek after blending with large tributary.
9	5.9	Small tributary at edge of composite aura.
9.5	3.2	Creek above confluence with master creek.
—	1.3	Master creek 0.3 km above confluence.
10	1.7	Master creek after blending with creek.
18	3.0	Master creek at lower end of composite aura, after influx of ground water and large tribu- taries ranging from 4.1 to 7.9 ppb U.

Standardization of appraisal techniques for the many types of environments requires detailed geochemical information from as many diverse types of uraniferous waters as possible. The great diversity in the large number of samples examined is shown by the index of selected major items, Table 16.2.

TABLE 16.2

Constituent	Maximum	Minimum
U (ppb) . . . . .	5,300	$<0.02 \pm$
Fe (total) (ppm) . . . . .	2,310	$<0.1$
Ca (ppm) . . . . .	1,190	0.6
Mg (ppm) . . . . .	1,520	0.1
Na (ppm) . . . . .	13,400	0.3
K (ppm) . . . . .	1,100	0.1
HCO <sub>3</sub> (ppm) . . . . .	2,630	0
SO <sub>4</sub> (ppm) . . . . .	8,820	0.7
Cl (ppm) . . . . .	25,000	$<0.1$
Total dissolved solids . . . . .	42,200	23
Total carbonate hardness . . . . .	7,250	2.0
pH . . . . .	9.3	2.5



Thermal springs are lower in uranium content than are cold waters under equivalent conditions. This is probably due to the increased chemical reactivity of hot waters and the removal of uranium minerals early in the life of the springs. The highest uranium content found to date is 7.0 ppb in the Alhambra hot spring in Montana. Cold water in a uranium prospect only a few hundred meters distant on the same mineralized structure contains 140 ppb U.

**Background concentration of uranium in water.** The background concentration of uranium in natural waters, expressed in parts per billion (ppb), is roughly analogous to the background intensity of radioactivity, expressed in milliroentgens per hour (mRh); but, as one measures uranium directly and the other does not, they are not to be equated. The standards of reference are entirely different.

For clarity two types of hydrogeochemical background are distinguished in appraising uranium deposits. The regional background is the average uranium content of waters in a given region that are not appreciably affected by dispersion auras. The areal background is the average for waters in a given area, ordinarily much smaller than a region, that are materially affected by dispersion auras, yet are not actually in or immediately adjacent to economic or near-economic deposits.

Regional background is represented by 108 of some 700 water samples from 10 states. The average of all 108 is 0.10 ppb, and this is thought to be reasonably representative of background for the United States. The observed maximum is 0.5 ppb, and the minimum is 0.02 ± ppb U, Table 16.3.

TABLE 16.3. REGIONAL BACKGROUND

State	Number of Samples	Uranium Content (ppb)		
		Average	Maximum	Minimum
Colorado.....	33	0.19	0.5	<0.1
Montana.....	22	0.16	0.3	0.1
Georgia.....	14	<0.1	0.2	<0.1
Washington.....	9	0.07	0.1	<0.02±
South Carolina.....	7	0.1	0.2	<0.1
Utah.....	7	0.10	0.2	<0.1
Wyoming.....	6	0.22	0.4	<0.1
Florida.....	5	<0.1	0.1	<0.1
Idaho.....	3	0.22	0.3	<0.1
North Carolina.....	2	0.1	0.1	0.1



Areal background is represented by 195 water samples from 9 states and 8 from Alaska. The average of the 195 samples is 0.80 ppb U, and this is thought to be reasonably representative for the uraniferous areas of the United States, although in the Colorado Plateau it may be considerably more. The observed maximum for all 203 samples is 2.5 ppb, and the minimum is 0.2 ppb U, Table 16.4.

TABLE 16.4. AREAL BACKGROUND

State	Number of Samples	Uranium Content (ppb)		
		Average	Maximum	Minimum
Montana.....	91	0.69	1.7	0.3
Colorado.....	52	0.62	1.8	0.3
Texas.....	32	1.47	2.5	<0.5
Utah.....	9	1.13	2.0	0.4
South Carolina.....	3	0.2	0.2	0.2
Florida.....	2	0.2	0.2	0.2
New Mexico.....	2	0.55	0.6	0.5
Wyoming.....	2	0.65	0.8	0.5
Idaho.....	2	0.65	0.8	0.5
Alaska.....	8	0.45	0.5	0.4

**Anomaly.** The threshold of anomaly—a rough guide to waters requiring further investigation—is about 1.0 ppb U, or 10 times the regional background in the western United States generally. In the tuffaceous rocks of the Great Plains it is about 2 ppb in surface waters and 5 ppb in ground waters. In the Colorado Plateau it is about 4 ppb in surface waters and at least 5 ppb in ground waters.

The threshold for uraniferous phosphate deposits is about 0.3 ppb U. This is not to be equated with the threshold level in other terranes, because it actually refers to phosphate deposits rather than uranium per se, which at best can be mined only as a by-product.

The upper limits of anomaly differ greatly between ground and surface waters, and also within each type, with differences in geochemical conditions. The following data concerning the range found in the two types refer only to true natural values unbeneficiated by evaporation or recent mining operations, the effects of which are discussed later.

Surface waters in most uraniferous areas ordinarily contain from 1 to 10 ppb U. The greatest content found to date in small streams is 32 ppb in Bishop Creek in southwestern Montana, 2 kilometers below drainage from a uraniferous



base-metal mine. In rivers the greatest content found is 4 ppb in the Sevier River below the Marysvale uranium-mining district in Utah. The chief controls in surface waters seem to be the extent of dilution by low-uranium waters from barren areas, and the pH. The pH in most surface waters sampled ranges from 5.5 to 7.5; a high uranium content does not occur in this pH range. The more acid the waters, other things being equal, the greater the uranium content.

Ground waters in most uraniferous areas ordinarily contain from 1 to about 120 ppb U. Those within the pH range of 5.5 to 7.5 contain moderate amounts, but strongly acid waters may contain very large amounts of uranium if they have access to sufficient uranium mineralization. The greatest uranium content found to date is 5300 ppb in water with a pH of 2.5 in a large uraniferous base-metal mine in Arizona.

The uranium content of any water must be appraised in terms of the net effect of the conditions controlling that particular water, including the degree of access it has had to uranium. Unevaluated data where uranium contents alone are quoted have little significance. For example, waters that contain as little as 4.8 ppb uranium are known from mines that have actually produced uranium, whereas waters from mines that have produced no uranium ore are known to contain more than 100 ppb U, and one very acid water in a mine that to date has produced no uranium contains the maximum found—5300 ppb U.

The observed range in uranium content of waters in mines that have produced at least some uranium ore is from 4.8 ppb at the Free Enterprise uranium mine in the Boulder batholith area of Montana, to as much as 535 ppb in some uranium mines of the Colorado Plateau where the waters have been beneficiated to some extent by recent mining operations and excessive evaporation caused by arid climate. The low content in the Free Enterprise mine water is the result of rapid circulation of a large volume of ground water that allows the unit volume of water minimum time to dissolve uranium.

The true natural uranium content of water in uranium mines under ordinary conditions is thought to range from about 15 to 400 ppb, but when pH is lower than about 4.0, the content may be much larger.

Uranium deposits differ in the amounts of major and particularly in the minor elements they contain. These differences inevitably modify the chemical nature of waters passing through them. Hence the location, size, and possibilities of deposits are appraised by the peculiarities of chemical makeup disclosed by analysis of the waters. This consists of semiquantitative spectrographic analysis for 60 elements, chemical analyses for major and some minor elements, and fluorimetric analysis for uranium. These data are interpreted with respect to the geologic controls such as faults, concealed bedrock groundwater dams, and permeability of formations.



**Seasonal fluctuations in uranium content.** The uranium content of waters fluctuates seasonally because of dilution by snow melt and storm waters low in uranium. Ordinarily the content is inversely proportional to the abundance of surface water, but it may be somewhat proportional if the surface water has taken up an abundance of uranium from dry-season efflorescences or dust. The fluctuation in ground water ordinarily is much less than in streams.

A typical example of fluctuations in smaller streams draining uraniferous areas is Prickly Pear Creek, Montana, at the mouth of its canyon. The uranium content at seasonal peak discharge in June 1954 was 1.5 ppb, but at low stage in September 1953 it was 4.2 ppb. A typical creek in the uranium-mining area of the Front Range near Denver, Colorado, contained 4.2 ppb late in November 1954 when drought had reduced the water supply materially, but the content was 1.5 ppb U in March 1955 as the result of dilution of ground-water increment by snow-melt water.

Seasonal fluctuations in the uranium content in shallow ground waters resemble those in surface waters, but in deep ground waters the fluctuations are less. Water from the Argo Tunnel that drains the uraniferous Central City mining district near Denver, Colorado, contained 76 ppb U in May 1954 when snow-melt water descending through old workings was diluting the ground water, 89 ppb in September 1954 when the ground-water level was low, and 81 ppb in April 1955 when dilution by surface water was unusually low because of drought.

**Effect of evaporation and mining operations.** The uranium content of water may be increased greatly by excessive evaporation, recent drilling or blasting, or disturbance of ground as in placer mining. The increase may be as much as several hundred times the true natural value. Evaporation effect ordinarily is negligible, but an arid climate, power ventilation in mines, or evaporation-basin conditions may have great effect.

Recent drilling or blasting may increase the uranium content as the result of comminution or fine grinding of uranium mineral to allow water to attack more surface area per unit volume per unit time. The increase is thought to range from about 25 to 250 times the true natural value, depending on the uranium content of the ground. The increase is about 25 times true natural value in one uraniferous Montana base-metal mine where conditions are closely controlled. In a uranium mine with rich ore near Denver, Colorado, the increase caused by drill water seeping through normally dry workings is about 250 times. The effect decreases more rapidly where drainage is good, but is thought to require about a year to be eliminated under ordinary conditions in mine workings. In drill holes the effect may last longer. The effect has been encountered in samples from deposits affected by placer mining in Idaho and Alaska, but its extent and duration are not yet known.



The effects of evaporation by mine ventilation and of drilling and blasting are commonly found together, as in the Sligo adit, which is in Chattanooga black shale in central Tennessee. A stagnant pool near the face, 150 feet from the portal, contained 690 ppb U when sampled; but after the pool was drained and samples were obtained from seepage in the walls, the uranium content was about 1 ppb. The joint effect of evaporation and mining was to increase the uranium content about 500 or 600 times the true natural value.

**Conclusion.** The large number of analyses now available establish hydrogeochemical exploration for uranium as a valid means of appraising the uranium possibilities of regional and local areas. The many factors that must be taken into consideration can be evaluated as suggested in the foregoing text. It is very apparent that the uranium content of a water by itself means little without geologic background and a satisfactory sample pattern in which to place the figure. Given the required information, however, the uranium content of natural waters, both surface and underground, should reveal the presence of much uranium ore at present undiscovered.

#### HYDROGEOCHEMICAL PROSPECTING IN THE U.S.S.R.\*

The radiohydrogeological [hydrogeochemical] method of prospecting for uranium deposits is based on the ability of this element and its disintegration products—radium and radon—to dissolve in natural waters and migrate together with them.

At present a large number of facts have been accumulated on the occurrence of radioactive elements in natural waters, and these facts have formed a basis for the development in the U.S.S.R. of the hydrogeochemical method of prospecting for uranium deposits. It was proved that in prospecting for uranium ore deposits the best and most easily interpreted results are obtained usually by studies of the water halos of the uranium dissemination; as to radium and radon, they also play an important part, but their properties differ from those of uranium, and consequently, their migration is often also different.

It has been proved that all natural waters contain uranium, though its concentrations vary in wide range, from  $\sim 10^{-8}$  gm/liter † to  $\sim 10^{-2}$  gm/liter. The uranium content in sea water is  $2 \cdot 10^{-6}$  gm/liter; in river waters it varies from  $\sim 10^{-8}$  gm/liter to  $\sim 10^{-5}$  gm/liter; in some undrained basins it runs as high as  $\sim 10^{-5}$  gm/liter.

The uranium content in underground waters varies very widely. Thus, in the spring waters from barren rocks it sometimes drops as low as  $\sim 10^{-8}$  gm/liter;

\* From Geneva Conference Paper 626, "Radiohydrogeological Methods in Prospecting for Uranium Deposits" by A. A. Saukoff of the U.S.S.R.

†  $10^{-8}$  gram per liter (of water) corresponds to a weight concentration of  $10^{-5}$  part per million (ppm) or  $10^{-2}$  part per billion (ppb). [Ed.]



in the mine waters of uranium deposits it reaches as high as several hundredths gm/liter. High contents of uranium (and often of radium and radon as well) are observed in underground waters which have passed through uranium deposits; in water enriched with uranium at the expense of deposits, the uranium content is usually between  $\sim 10^{-5}$  and  $\sim 10^{-3}$  gm/liter, and sometimes rises as high as  $\sim 10^{-2}$  gm/liter.

Uranium enters the natural waters from various rocks through which these waters migrate, as well as from deposits in which it usually occurs as an independent mineral. This is proved both by observations in nature and by special experimental studies of the solubility of uranium minerals and of the leaching of uranium from rocks by various reagents, including reagents approaching natural waters in their properties. The amount of uranium that passes into solution depends on many factors—among others, on its concentration and forms of occurrence in the rocks and deposits, on the chemical composition of the solutions (including the gases dissolved in them, especially oxygen), on the flowing rate of the solutions, etc.

Proceeding from the high concentrations of uranium in its deposits, compared to rocks, and taking into account the relatively high solubility of its ore minerals, it is evident that solutions washing the uranium deposits should as a rule be enriched in uranium, as well as in other radioactive elements, in comparison with the solutions which migrate in ordinary rocks. This, indeed, is often the case with waters that have passed through deposits. Waters that circulate under conditions strongly promoting reduction are an exception: they do not become enriched in uranium, but contain increased concentrations of Ra and Rn. The enrichment of water halos, connected with deposits, in uranium or other radioactive elements makes it possible to solve the reverse problem, viz., to prospect for uranium deposits by studying the content of radioactive elements in underground and surface waters.

Given favorable conditions, waters enriched in radioactive elements may come out on the surface in the lower part of the relief as springs, or may be struck by mine workings, drill holes, wells, etc. The content of radioactive elements in them will depend on the length and nature of the way by which the waters came from the deposit; they are richest in the vicinity of the deposit; at various distances from it they may mix with poor waters from barren rocks, and the concentration of radioactive elements in them will decrease, but still will remain anomalously high compared to ordinary waters circulating among rocks.

Hydrogeochemical investigations consist of three main kinds of work: sampling the waters, determining the content of radioactive elements in them, and interpreting the results.

In order to reveal waters anomalously rich in radioactive elements, samples of water are taken from all the springs, streams (at various points), wells, drill



holes, and other sources of water in the region being prospected for new deposits or ore bodies. Samples of water are taken also at all places of exposure in mine workings at new sites, from cracks, drill holes, etc. In some regions where there are few water sources, special pits of not very great depth or drill holes are sunk for the purpose of sampling underground waters.

In view of the seasonal changes in the content of radioactive elements which take place in underground waters during the year, hydrogeochemical investigations are carried out with a view to taking the water samples from each small area in the course of a comparatively small time interval of the same season. Furthermore, in the regions where work is carried out on typical water sources systematic observation is organized on the content of uranium or other radioactive elements in the water during the entire period of field work. This facilitates a more correct analysis of the great amount of facts collected over large areas as a result of water sampling at various seasons.

When sampling natural waters, attention is directed mainly at determining the uranium content. A large part of the samples are analyzed also for radon. Radium is determined only in a few selected samples, and in all cases when the water samples show high uranium or radon content.

In areas where reducing conditions develop in the waters, for instance, in waters circulating in highly bituminous rocks, determination of radium and radon in all the samples is obligatory. The reason for this is that under such conditions uranium ores are not dissolved perceptibly by the waters, so that the latter, though they may have passed through ores, will not be nearly as high in uranium; but in this case they will always be anomalously rich in radium and radon (though the latter disintegrates rather quickly, so that several hundred meters away from the ore its content will not be extraordinarily high).

In cases where the waters of springs, streams, or other water sources are found to be anomalously high in uranium and other radioactive elements, a more detailed hydrogeochemical investigation is carried out over the watershed in which these waters have their source, supplemented by prospecting by geophysical and other methods.

Methods based on the uranium adsorption from natural waters by some adsorbent are used for the determination of small amounts of uranium in natural waters. The uranium sample thus adsorbed is determined by means of luminescent (fluorimetric) or colorimetric analysis. The content of the element in the waters can be determined quite accurately, quickly, and easily, so that properly equipped field laboratories handle satisfactorily the mass water sampling done by field and prospecting parties.

The most complicated part of a hydrogeochemical investigation is the interpretation of the data obtained by the sampling of the water sources. The



interpretation of facts is based on the principle of degree of anomaly, the essence of which consists in the following:

The mass sampling of the water sources gives sufficient grounds to establish the normal content of uranium and other radioelements in the waters (the so-called natural hydrogeochemical background). The natural hydrogeochemical background is not established as a set of universally applicable values of the radioelement content in underground waters, but is determined separately for each definite type of rock, separately for each district. When rocks of the same kind occur under substantially differing climatic conditions a separate natural background is established for each climatic zone. This is especially important in mountain regions, where the vertical climatic zones often rapidly change.

When establishing the background uranium content in the underground waters of any given rocks, the hydrogeochemical conditions under which those rocks occur are always taken into consideration—whether these conditions promote oxidation with free oxygen occurring in underground waters, well below their level, whether they are bituminous and promote reduction, and whether they otherwise promote the solution of the ores and the migration of uranium in the underground waters or interfere with them. The natural background itself varies over a wide range, from  $\sim 10^{-8}$  to  $5 \times 10^{-5}$  gm/liter of uranium, and thus, what is a natural hydrogeochemical background in some districts will be a strongly anomalous phenomenon in others, if differences in the water-bearing rocks and climatic and other conditions are not taken into consideration. Thus, for instance, in regions with a dry climate, the underground waters in the zone of intensive water exchange often contain  $\sim 10^{-5}$  gm/liter uranium, as a result of their passage through barren rocks not substantially enriched with uranium. In anomalous waters which have passed through ores, the uranium contents increase to  $\sim 10^{-3}$  gm/liter and more. In adjacent districts the waters of the same rocks, but under climatic conditions of high altitudes, usually contain  $\sim 10^{-7}$  to  $10^{-8}$  gm/liter of uranium, while anomalous waters formed by passing through uranium mineralization often contain only  $\sim 10^{-5}$  to  $5 \times 10^{-4}$  gm/liter.

Thus, the hydrogeochemical background is established individually for the underground waters of each kind of rock, for different climatic zones, for definite seasons of the year, for different hydrogeochemical conditions, taking into account the geomorphological and other differences between districts.

When the usual background content of uranium or other radioactive elements in the underground waters is known, there is no difficulty in revealing the anomalous water sources, in which the content of these elements in the water by an order or more exceeds the natural background (for the same season), for instance,  $5 \times 10^{-5}$  gm/liter of uranium or more with the usual uranium content in the water of these rocks averaging  $5 \times 10^{-6}$  gm/liter.



An estimation of the research significance of the revealed water anomalies is made by careful analysis of the possible causes and conditions for their occurrence. In each case an individual assessment is made of the geological structure, the hydrogeological conditions and the geomorphological and other peculiarities of the watershed area from which the anomalous source draws its waters.

The first thing that has to be established is whether the watershed area contains any unusual rock masses, of minor area but with high uranium content, which could raise the natural background for the mixed waters without any anomaly in uranium content really existing.

Knowledge of the geomorphology of the district is important because it enables the time of openness of the geostructure of the district to be established, thus making it possible to determine the difference of intensity and depth effect on rocks and ores of active water exchange. In areas with well-developed weathering zones, where the deposits are intensively oxidized and washed by underground waters to a depth of several tens of meters, the uranium content anomalies are, as a rule, not so pronounced. Therefore, in some cases in well-washed structures, water anomalies with an excess of only half an order over the natural background are significant from a prospecting standpoint. For instance, a uranium content in waters of shallow circulation, springs, wells, etc., amounting to  $6 \times 10^{-6}$  to  $5 \times 10^{-5}$  gm/liter with a background of  $\sim 10^{-7}$  gm/liter may serve as an indication of a deposit which has survived erosion by underground waters at some depth or other.

In districts with already known deposits the peculiarities of the ores, their composition, permeability, and other factors influencing the ore solution by underground waters should be taken into account. Thus, for instance, compact pitchblende or amorphous oxide ores enrich the underground waters in radioelements less than loose amorphous oxide ores. Water anomalies arising from the solution of compact ores are less salient, so that the uranium content in anomalous waters exceeding the natural background by only one-half to one order may indicate commercial ore occurrences.

In interpreting water anomalies a more complete analysis of given anomalous waters and the surrounding hydrogeochemical background must be available (Ra and Rn content, chemical composition, etc.). Raised concentrations of radium in anomalous waters are also adequately good indications for prospecting, while a high radon content is indicative that the uranium mineralization which caused the water anomaly is comparatively close to the water source in which this content was observed.

In some cases a more correct analysis of the causes of a water anomaly can be made by using the data on the chemical and gaseous composition of the anomalous waters, inasmuch as anomalous waters sometimes differ in this respect from the surrounding waters. Thus, for instance, in some districts



waters anomalous in uranium are distinguished by a high sulfate content, since uranium ores are usually associated with sulfides.

In interpreting water anomalies it is specially important to take into consideration the hydrogeological conditions over the area feeding these waters (the direction of flow of the anomalous waters, etc.). If the anomalous waters are considerably diluted, especially when they join streams, in some cases an excess of uranium content of from one-half to one order, i.e., five to ten times compared to the natural background, may be considered a favorable sign in prospecting.

In deciding upon the research significance of water anomalies, climatic peculiarities of the district should be taken into consideration. Thus, for instance, in a district with a dry climate an anomalously high uranium content may occur in the waters due to the evaporation of soil waters; this leads to the formation of false anomalies.

In some cases, to establish the research significance of water anomalies, especially in districts with highly developed loose formations covering the outcrops of the lode rocks, special work is done with a view to delineating the halos of anomalous waters in order to find their sources and determine the points and extent of possible uranium mineralization. For this purpose pits or drill holes are sunk to strike the underground waters.

The final decision as to the prospecting significance of water anomalies is made after all the data on the geology, mineralogy, and geochemistry of the districts under consideration have been taken into account. After this, the necessary geophysical, hydrogeological, and other kinds of geological and prospecting investigations are started in the districts.

The use of the hydrogeochemical method has led to the discovery of new ore-bearing districts and deposits, as well as new ore bodies in deposits already being mined or prospected.

#### USE OF WATER SAMPLING IN LOCATION OF POTENTIAL URANIUM SOURCE BEDS \*

As part of the investigations of uranium occurrences in carbonaceous rocks and sandstones a large number of water samples were collected for analyses of their uranium and other trace-metal content in several areas in the Great Plains and in Tertiary basins of the Rocky Mountain region. The samples were obtained during the period 1950 to 1954 to accumulate data on the uranium content of water in different rock types and stratigraphic units and to evaluate water sampling as a technique in search for uranium deposits. The waters

\* From Geneva Conference Paper 507, "Water Sampling as a Guide in the Search for Uranium Deposits and Its Use in Evaluating Widespread Volcanic Units as Potential Source Beds for Uranium" by N. M. Denson, H. D. Zeller, and J. G. Stephens, U.S. Geological Survey.



sampled were collected mostly from seeps, springs, and wells and are mostly derived from underground sources. A smaller number of surface-water samples collected from streams, lakes, and reservoirs were difficult to evaluate. Attention was directed mainly toward terranes underlain by tuffaceous sedimentary rock equivalents of acid volcanic rocks, fluvial arkosic sandstone, and shale, and areas containing known secondary uranium occurrences.

Pint samples of ground water were collected in polyethylene bottles, and acidity of the water was determined in the laboratory with a pH meter with a glass electrode. The uranium content was determined by ethyl acetate extraction method as follows: An acidified aliquot of the sample, usually 100 to 500 ml, was evaporated nearly to dryness and then diluted with distilled water acidified with nitric acid. An aliquot of this solution was salted with recrystallized aluminum nitrate, and the uranium was extracted with ethyl acetate. The extract was then burned off in a platinum dish, and the residue was fused with a sodium fluoride carbonate flux. A sensitive fluorimeter was used to compare the fluorescence of the unknown with standards treated in a similar manner, and the uranium content was calculated in parts per billion. The probable limits of accuracy of this method range from about 1 ppb (parts per 1,000,000,000) for samples containing 10 ppb, to about 10 ppb for samples containing 100 ppb uranium.

**Uranium in ground water.** Results of systematic sampling in four areas in South Dakota and Wyoming showing the average uranium content of ground water in the different geologic environments in each area are summarized in Table 16.5. The variation in uranium content of water is shown on the generalized geologic maps (Figs. 16.1 to 16.4).

At Slim Buttes in southwestern Harding County, South Dakota (Fig. 16.1) some lignites of Paleocene age contain small amounts of uranium. Uranophane and autunite locally impregnate carbonaceous sandstones in rocks of the same age. Both the uranium-bearing lignite and sandstone closely underlie tuffaceous rocks of Oligocene and Miocene age. Carnotite occurs locally in tuffaceous sandstone and claystone of the Oligocene rocks.

In the Powder River Basin in eastern Wyoming (Fig. 16.2) carnotite and uranophane occur in fluvial sandstones of Eocene age. Erosional remnants of Oligocene and Miocene tuffaceous sediments in the basin indicate that most of the basin was once covered by these sediments. In the Gas Hills area, Wyoming (Fig. 16.3), uranium deposits occur in the Wind River formation of Eocene age, with the exception of two minor occurrences in subjacent Mesozoic rocks. Meta-autunite and an unnamed yellow uranium phosphate are the most common ore minerals and generally occur as interstitial fillings in coarse-grained, arkosic sandstone of fluvial origin. Metazeunerite, uraninite, and other uranium minerals also are found in the area. In the Crooks Gap area, Fremont County, Wyoming (Fig. 16.4), uranium minerals, prin-



TABLE 16.5. SUMMARY OF URANIUM CONTENT OF 277 WATER SAMPLES FROM AREAS DESCRIBED IN THIS REPORT

Units from Which Water Was Sampled		Average Uranium Content of Water (ppb)	Average pH
<b>Slim Buttes, South Dakota:</b>			
Oligocene and Miocene.....	49	34	8.9
Cretaceous and Paleocene.....	34	4	8.9
Mineralized areas.....	5	72	8.6
Total samples.....	88		
<b>Powder River Basin, Wyoming:</b>			
Oligocene and Miocene.....	28	46	8.1
Eocene and Paleocene.....	25	4	—
Mineralized areas.....	4	84	—
Total samples.....	57		
<b>Gas Hills, Wyoming:</b>			
Oligocene and Miocene.....	6	12	7.92
Eocene and older.....	37	6	7.86
Pre-Cambrian and Tertiary intrusives ..	3	1	7.43
Mineralized areas.....	16	98	6.81
Total samples.....	62		
<b>Crooks Gap, Wyoming:</b>			
Miocene.....	9	19	—
Eocene and older.....	55	4	7.5
Mineralized areas.....	6	124	7.5
Total samples.....	70		

cipally uranophane and minor amounts of autunite, impregnate arkosic sandstone of the Wasatch formation of Eocene age.

**Other trace elements.** Trace elements other than uranium were determined by chemical and spectrographic analyses of residues obtained by evaporation of large water samples from ground water in late Tertiary tuffaceous units from localities in Kansas, Montana, South Dakota, and Wyoming. A comparison of the trace elements present in these residues with those elements present in the uranium minerals found in the region shows that most of the elements in



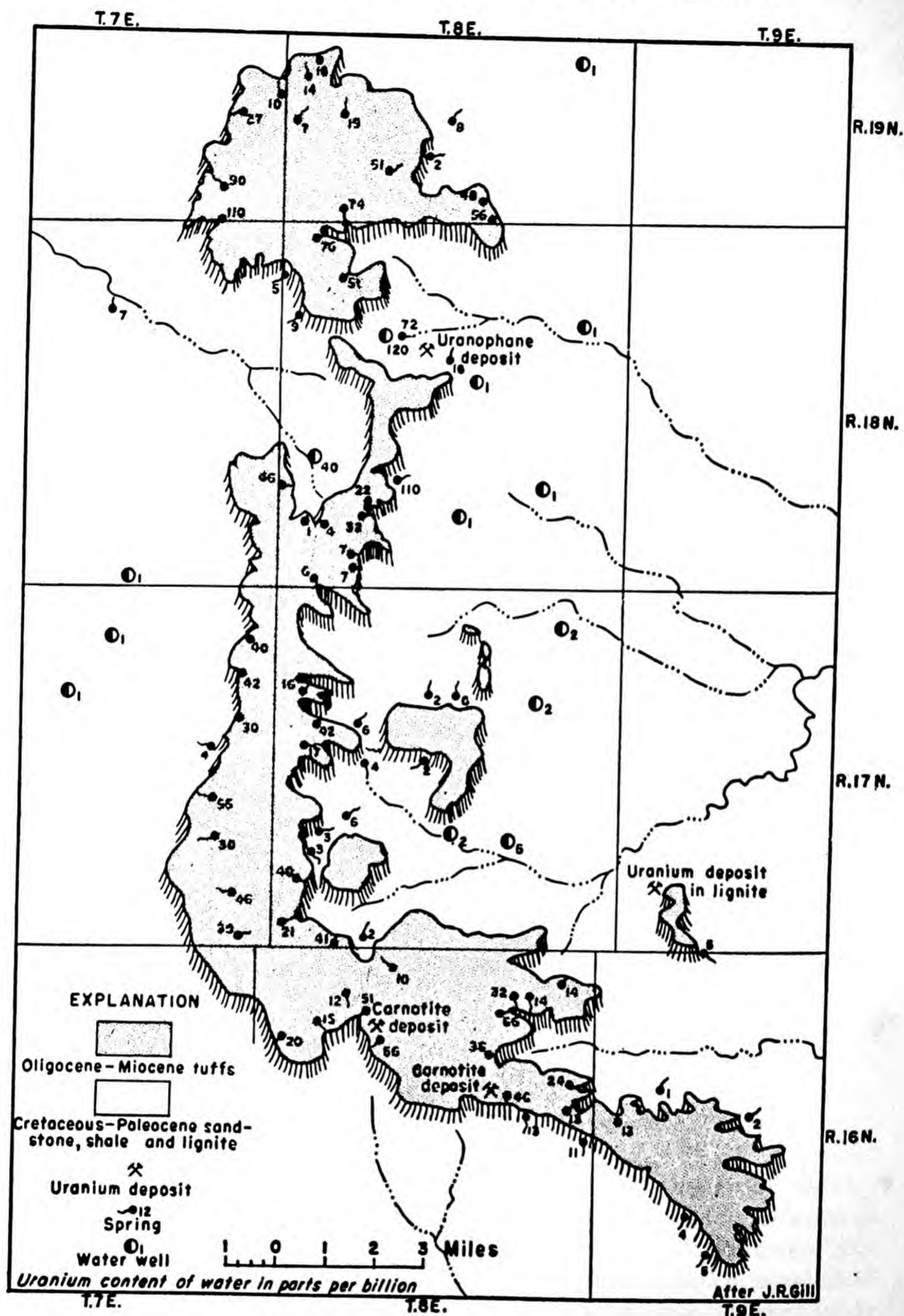
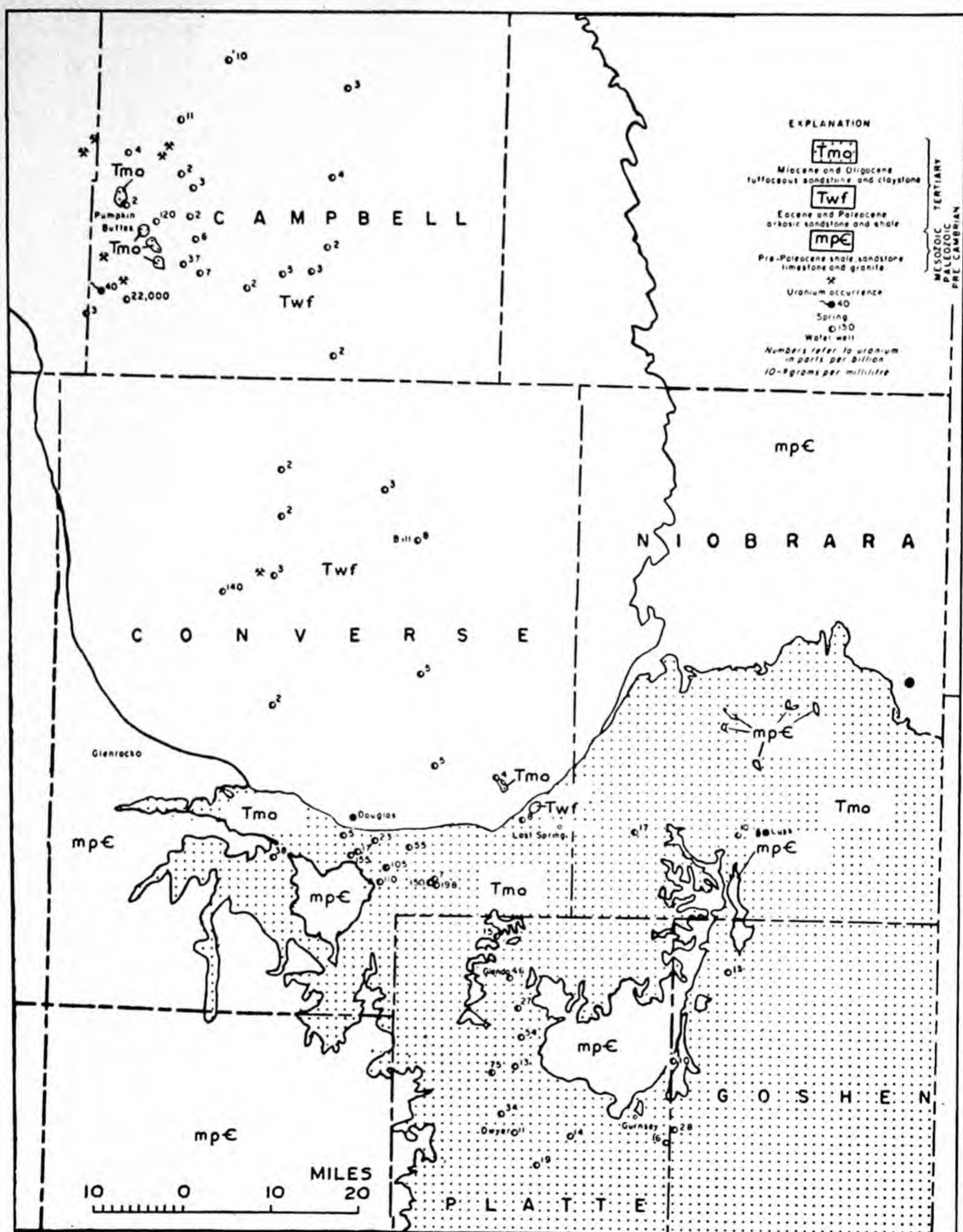


FIG. 16.1. Distribution of uranium in water from Slim Buttes and vicinity, Harding County, South Dakota.





*After M. L. Troyer*



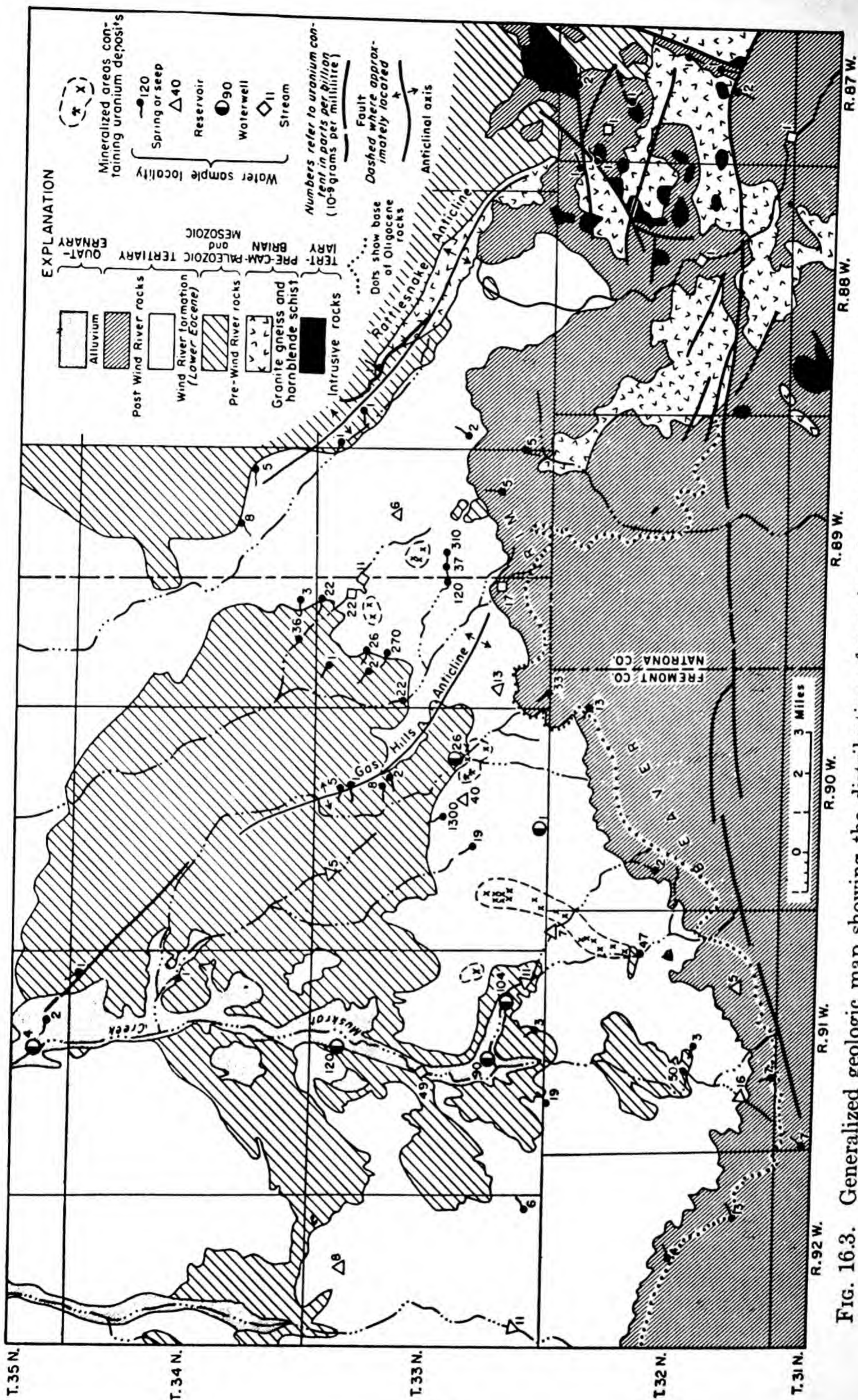


Fig. 16.3. Generalized geologic map showing the distribution of uranium in water in the Gas Hills area, Wyoming.



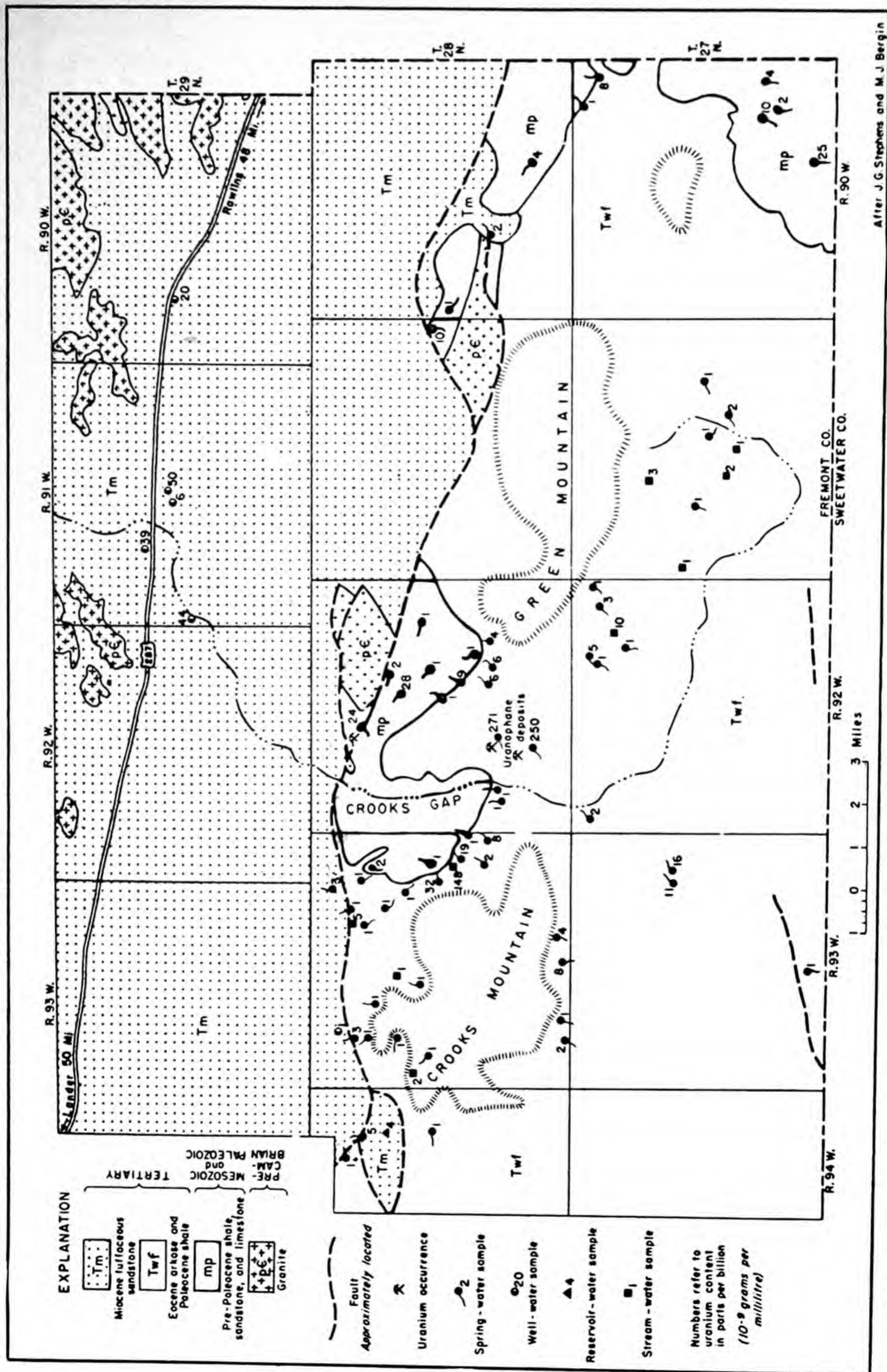


Fig. 16.4. Generalized geologic map showing the uranium content of water in the Crooks Gap area, Fremont County, Wyoming.



TABLE 16.6. QUANTITATIVE ANALYSES OF SELECTED TRACE ELEMENTS IN WATER

Rock Unit and Age	Area	Parts per Billion								Ppm		pH
		As	Se	P	Cu	V	Mo	Zn	U	Na	Ca	
Late Tertiary tuffaceous rocks: Ogallala fm. Pliocene	Smoky Hill, Kans.....	28	14	<42	10	10	477	70	49	230		7.8
	Miller Hill, Wyo.....	2	<1	732	3	17	10	37	14			
Browns Park and Arikaree fms. Miocene	Long Pine Hills, Mont.....	16	32	38	4	85	2	11	10	86		8.8
	Sweetwater Arch, Wyo.....	6	1	26	9	42	4	66	50		29	7.6
	Saratoga Basin, Wyo.....	<7	2	71	5	11	24	43	16			7.4
	Poison Basin, Wyo.....	60	7	82	9	5	0	32	11	368		7.5
	Washakie Basin, Colo.....	19	<4	96	13	6	0	2882	8			7.7
White River fm. Oligocene	White River Badlands, S. Dak.....	20	4	15	8	17	170	25	13	125		8.5
	Southern Black Hills, S. Dak.....	19	5	22	3	15	15	27	8	132		8.2
	Powder River Basin, Wyo.....	18	11	44	14	139	30	71	150	255		8.6
	Beaver Divide, Wyo.....	11	1	19	3	13	1	<7	13	71		7.4
Early Tertiary arkosic rocks in mineralized areas: Wind River and Wasatch fms. Eocene	Gas Hills No. 1, Wyo.....	<11	<1	?	18	3	3	233	270			3.9
	Gas Hills No. 2, Wyo.....	<25	10	<125	113	8	85	50	310	503		7.7
	Crooks Gap, Wyo.....	<3	1	14	9	2	0	19	271	30	53	8.3



uranium minerals are also present in the water residues. For example, the important secondary minerals common to a number of the deposits in the areas considered here are carnotite  $[\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 1-3\text{H}_2\text{O}]$ , autunite  $[\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 10-12\text{H}_2\text{O}]$ , and metazeunerite  $[\text{Cu}(\text{UO}_2)_2(\text{AsO}_4)8\text{H}_2\text{O}]$ . In addition to uranium, ore samples contain varying amounts of vanadium, phosphorus, arsenic, and copper. Analyses of the water residues from the tuffaceous units shown in Table 16.6 indicate the presence of more than normal amounts of these elements.

**Summary of results.** The uranium contents of ground water of the different sedimentary terranes in the areas studied show marked variations. The highest concentrations of uranium in ground water are generally found in areas near known uranium deposits; greater than normal concentrations of uranium in ground water are found in acid tuffs and tuffaceous sedimentary rocks of Oligocene and Miocene age; and ground water from arkosic and other sedimentary terranes that are not near uranium deposits generally contain only a few parts per billion of uranium. The most highly mineralized water in tuffaceous terranes has an alkaline pH range of 7.5 to 9.5. In general the more alkaline waters from these rocks carry the most uranium in association with proportionately larger amounts of sodium and calcium, the Oligocene being more sodic and the Miocene more calcic. The relationship of other trace elements to the uranium content of these waters has not been determined, but laboratory data show that they also contain greater than normal amounts of molybdenum, vanadium, copper, phosphorus, zinc, and arsenic.

The relatively high uranium concentrations in the water from the Oligocene and Miocene units probably is due to the uranium content of its tuffaceous constituents. These rocks are mostly water-laid and contain large quantities of air-borne volcanic sediments. Owing to their high porosity and permeability, water is permitted relatively easy circulation. Although the uranium content of these rocks varies markedly from place to place as well as within short distances along the same stratigraphic horizon, chemical analyses show a maximum uranium content of 0.0030% and an average of about 0.0015%. Uranium disseminated in these rocks may have been an important primary source of uranium later concentrated in the secondary deposits in the underlying sedimentary rocks through ground-water circulation.

#### SELECTED REFERENCES FOR CHAPTER 16

- Grimaldi, F. S., I. May, and M. H. Fletcher, 1952: *U.S. Geological Survey Fluorimetric Methods of Uranium Analysis*. U.S. Geological Survey Circular 199.
- Judson, S., and J. K. Osmond, 1955: Radioactivity in ground and surface water. *Am. J. Sci.* 253:104-116.
- Ostle, D., 1954: Geochemical prospecting for uranium. *Mining Mag.* 91(4):201-208.



# *Chapter 17*

---

## EXPLORATION DRILLING

---

---

\* Exploration drilling for uranium usually involves either a grid or a "fence" (row) of holes. The grid pattern is used where little is known about the area and it is desired to make subsurface favorability criteria studies. It is also used in testing for ore bodies not confined to a linear paleostream channel and having random distribution as well as variable size and shape. As information is gained through drilling on a grid, definite trends of either favorable ground or ore deposit alignment are established and a fence-drilling pattern oriented perpendicular to such trends is used. Hole spacing is greater when searching for favorable ground than when looking for ore bodies within a favorable area. There are great differences in size of both ore bodies and favorable areas; hence no definite rule can be set for spacing of holes in the search for either. The quest for purely geological information may not require definite spacing, although in areas of rapidly changing structure or lithology, hole spacing must be rather close to permit subsurface correlation.

In the case of ore bodies in paleostream channels, the problem is to follow the concealed channel back from the outcrop by drilling. A fence pattern is usually most economical, and once the trend of the channel is determined by the first row of holes behind the outcrop or from any two adjacent rows of holes, spacing between fences can be increased. Once the channel is located, further drilling within the channel—the area of favorable ground—in search of ore bodies may be on a grid pattern for uniform coverage. This may be followed by closer-spaced offsetting of mineralized grid holes in order to outline ore bodies.

\* From Geneva Conference Paper 513, "Drilling Techniques in Search of Uranium" by J. W. Chester, U.S. Atomic Energy Commission. Selected references are listed at the end of the chapter.



## TYPES OF DRILLING \*

**Diamond drilling.** The diamond core drill of standard mining type is that most frequently used in search of uranium on the Colorado Plateau.† Most have a hydraulic feed, are truck-mounted, and are motivated either by the truck motor or a separate motor. Usually, the water and hydraulic pumps, and in some instances a water tank to supply water to the drill, are also mounted on a truck bed. Trucks vary in type, but either the tandem or four-wheel-drive truck is best suited to the rough country in which the rigs must work. The larger rigs have masts, raised or lowered by hydraulic cylinders, tall enough to allow 30-foot pulls of drill rod.

Rate of drilling for this type rig is slower than for many others, but averages from 20 to 30 feet a day at depths over 800 feet, and from 60 to 100 feet a day in shallow holes. Although diamond core drilling is more expensive than other types, the capital outlay for equipment is less than that for a rotary drill.

The double-tube, swivel-type core barrel is used almost universally on the Plateau; modifications which have increased its efficiency include enlarging of the space between inner and outer barrel so that fluid may pass more readily, and extending the inner barrel nearer to the bit face to reduce the amount of washing of core. A few years ago, much of the drilling was done in AX size; now, almost all is BX or NX. Coring in the larger diameters allows greater core recovery in friable sandstones as well as enabling the driller to complete holes to greater depths. Furthermore, the larger the drill rod, the less the vibration and consequently the greater the core recovery.

In most cases, water is used as the circulating medium to cool the bit and to lift the cuttings to the surface. Drilling muds have not been used extensively on the Plateau.

**Rotary drilling.** Air, as the circulating medium, is now used more than in the past, and in dry ground, where it can be used, it results in faster drilling and lower cost. Although rotary drills are used chiefly for drilling where core is not desired, they can be adapted to take NX or larger core. Because they use lower rotational speeds, coring is slower than with the standard diamond core drill. Drilling dry, the rotary will average 300 to 600 feet a day, a rate which surpasses that of any other type drill. As much as 1300 feet has been drilled during an 8-hour shift. Drilling wet, the rate of penetration is slower.

The chief advantages of air rotary drilling are its low cost and high speed. Rotary drilling costs from one-half to one-sixth as much as diamond core

\* Geneva Conference Paper 513.

† This was true, until recently, of exploration drilling as contrasted with development drilling, for which the cheaper non-core methods were favored. In recent years rotary and percussion non-core drilling has also come into wide use in exploration. [Ed.]



drilling (Table 17.1), although the capital outlay for a rotary drill is greater than for a diamond drill.

**Percussion drilling.** The air percussion deep-hole drill, the "wagon drill," has been developed in its present form almost entirely on the Colorado Plateau. The drill, hoist, and compressor customarily are mounted on a truck. The rig consists of a drifter-type or large sinker-type air percussion drill, mounted on a slide attached to a mast. Up and down motion of the drill is controlled by either a vane- or piston-type air motor through an endless chain attached to the drill. A cross-type, tungsten carbide insert bit is used. With the large hammers and larger multistage compressors, this type of drill, in dry formations, can drill readily to a depth of 250 feet; maximum depth attainable is about 350 feet. Drilling costs are low, as is the capital expenditure.

The wagon drill is even more limited by wet ground than is the dry rotary drill. With the latter, when excessive moisture is encountered, it is possible to change to wet drilling. Attempts to use water as a circulating medium with the wagon drill have not been successful.

Underground exploratory drilling is usually accomplished with a percussion drill, and holes, usually limited to 100 feet in length, are fanned ahead of or to the sides of an underground heading.

**Other techniques.** Some drilling is done with cable tool drills or spudders. This type uses a chopping bit suspended on a cable and is given an up and down motion by an eccentric drive. Its chief use has been as an auxiliary to diamond drilling where such is hampered by unconsolidated overburden. A few calyx drills have been used on the Plateau, chiefly for drilling utility and air shafts to ore bodies. Hole diameters range from 24 to 72 inches.

### EVALUATION OF METHODS

More and better geologic information is obtained through use of the diamond drill than from other types used on the Colorado Plateau. In dry drilling, where no core is obtained, much information is lost. However, it is possible by careful study of the cuttings to obtain some subsurface lithologic information, and even if all samples are lost, information can be obtained by electric and gamma-ray logging of the hole.

The greatest problem of dry-hole drilling is moisture. The moist particles can be blown from the hole, but after the bit has passed the moist zone, the dry cuttings adhere to that zone, cutting off air circulation and usually sticking the tools.

Dilution of samples is another problem in dry drilling with either rotary or percussion drills. Unless there is a minimum of overburden and the underlying formations are well cemented, material falling from the sides of the hole



can lead to erroneous interpretation of the composition of the beds drilled.

No adequate sampling method suitable for use with small rigs has been developed for wet rotary drilling. The rapid drilling rate and attendant necessity for mobility of sampling equipment make the standard methods of collection sludge samples impractical. With this type of drilling, gamma-ray logging and electric logging must be relied upon to give subsurface information.

Standard hole sizes most frequently drilled with diamond drills on the Plateau are  $2\frac{3}{8}$  to 3 inches. Most rotary-drilled holes are larger, being  $3\frac{7}{8}$  to 5 inches. A minimum hole size of  $2\frac{3}{8}$  inches is necessary to permit logging of the hole by most radiation detection equipment since the probe of the scintillation gamma-ray logging equipment most frequently used is 2 inches in diameter.

Of the three types of drilling commonly employed on the Colorado Plateau, diamond core drilling is the most expensive in cost per foot for equivalent depths. Rotary and percussion drilling costs are about equal and range from approximately one-half to one-sixth the cost of diamond core drilling. Penetration rates for percussion and rotary drilling are approximately three to eight times the rate for diamond core drilling. Table 17.1 lists prevailing prices for drilling on the Colorado Plateau showing variances for type of drill and depth range.

TABLE 17.1. AVERAGE DRILLING PRICES, PER FOOT, COLORADO PLATEAU AREA

Depths	Diamond Drill Core	Diamond Drill Non-Core	Rotary- Wet Drill	Rotary- Dry Drill	Non-Core Percussion Drill
0-100	\$1.75-\$2.50	1.00-1.75	1.25-1.75	.40-1.00	.60- .75
100-200	\$1.85-\$2.75	1.50-2.25	1.25-1.75	.60-1.25 *	.75-1.00 *
200-300	\$2.75-\$3.50	2.00-2.75	1.50-2.50	1.25-2.00 *	1.25-2.00 *
300-400	\$3.00-\$4.00	2.50-3.00	1.50-2.50	1.25-2.00 *	2.00-3.00 *
400-500	\$3.50-\$5.50	3.00-4.00	2.00-3.00	2.00-3.00 *	—
500-750	\$5.50-\$7.00	3.50-4.50	2.50-4.00	†	—
750-1000	\$7.50-\$9.00	4.50-6.00	4.00-5.00	†	—

\* Holes for which completion is not guaranteed if wet ground is encountered.

† Quotations below 500 feet are not reliable owing to wet ground conditions.

Inherent in the direct cost per foot of drilling are related costs of operating equipment and supplies. For a diamond core drill, these are the most expensive. Water for circulation is an additional expense for core drilling, either by diamond or rotary drills, and on the Colorado Plateau most drilling areas are remote and water is scarce. Of the three major types of drilling, operating



equipment and supplies for the percussion type are the most economical and easiest to obtain.

#### OUTLINING FAVORABLE ZONES USING WIDELY SPACED CORE DRILLING \*

Subsurface mapping techniques for outlining zones favorable for the occurrence of uranium-vanadium ores were tested in the Cottonwood Wash mining area, San Juan County, Utah, by holes spaced 500 to 1000 feet apart in the search for the small uranium deposits in the Morrison formation. The techniques employed may be useful in uranium search in other areas where outcrops are few or nonexistent.

**Geology.** The Cottonwood area is on the east flank of the Comb monocline where the eastward dip of the sedimentary rocks flattens from  $6^{\circ}$  near the monocline to  $1^{\circ}$  near the mines. On the eastern flank of the Comb monocline and in the drilling area, the formations range in age from the lower Jurassic Navajo sandstone to the upper Cretaceous Mancos shale. The Jurassic Bluff sandstone pinches out north and east along an irregular line through the Cottonwood drilling area. Of special interest is the overlying Morrison formation, which includes the Salt Wash, Westwater, and the Brushy Basin members. Sandstone, siltstone, and mudstone beds of the Salt Wash total approximately 210 feet in thickness in the mining area. They interfinger with the brown Recapture shales about 12 miles to the south. The Westwater sandstone is approximately 150 feet thick and pinches out a few miles north of the Cottonwood mining area. The Brushy Basin shale is the uppermost shaly member of the Morrison and averages 400 feet in thickness.

Vanadium and uranium deposits in the Cottonwood Wash area are mostly of the carnotite type; mill settlement sheets indicate an average ratio of vanadium to uranium of 10 : 1.

**Drilling.** Drilling to discover and block out ore bodies was done over an area of approximately 11 square miles.

Mapping of stream lineation and cross-bedding indicated that the Salt Wash streams flowed from west to east, which agreed with the regional trends established by Craig and others.

The drilling program was designed to extend geologic information east of the known mines and under deeper cover. Holes were drilled on 500-foot centers along north-south lines, spaced approximately 1000 feet apart along the indicated easterly direction of flow of the Salt Wash streams. Drilling depths ranged from 300 feet in the western portion to 850 feet in the eastern

\* From Geneva Conference Paper 516, "Subsurface Techniques for Outlining Favorable Zones Using Widely Spaced Core Drilling" by R. K. Pitman, P. H. Dodd, and C. W. Tom of the U.S. Atomic Energy Commission.



portion of the drilling area. Construction of subsurface maps of the area was supplemented by data taken from previous drilling in the area.

**Hypothesis on which techniques were based.** Geological investigation of the Salt Wash member has resulted in a concept of Salt Wash deposition by a multitude of anastomosing water courses which became filled with sand and sub-sand-size particles. The resulting deposition throughout Salt Wash time formed sediments that are today represented by tens to hundreds of feet of interbedded sandstone and mudstone.

Facies of fluvial deposits are believed to reflect environments of deposition in various zones in and adjacent to streams: fast-water channel zones, slow-water channel margin zones, and slack to semistagnant flood plain zones which were periodically inundated. Each facies is elongate parallel to flow direction, thus abrupt facies changes are observed in directions normal to the flow. Many facies, both similar and varied, are superimposed one above the other throughout the Salt Wash section. No extensive time horizons are recognizable within the Salt Wash member, and rock units do not represent exact time units. Rapid lateral facies changes resulting from different environments of contemporaneous deposition of sandstone and mudstone require acceptance of different rock types within small time units.

The direction of flow and deposition by a single stream in a restricted time interval is not necessarily the same as the mean direction of all the Salt Wash streams in one locality. Lack of recognizable time units requires correlation of rock units within a limited area, with subsequent division into depositional units or cycles. These are believed to represent limited time intervals.

If such a depositional unit is found to contain uranium deposits, and is suspected of containing others, it becomes necessary to trace this unit with a minimum number of drill holes. If several such units are known to be ore-bearing, each must be treated as a separate entity. This is particularly true when the facies within a single depositional unit are to be projected.

As the thickness of depositional units is not constant, the unit, rather than a constant thickness, is believed to be the best vehicle in subsurface mapping. Mapping of a single unit is preferred over mapping several combined units or the entire Salt Wash member. Mapping a combination of units results only in the assumed distribution of a synthetic mean-facies of a number of non-coeval discrete units.

It has been assumed that in general during a single depositional cycle the first sediment laid down is sand in the channel and mud on the flood plain; and that as the depositional cycle progresses, the channel zone becomes filled with both sand and mud, and the final layer of the unit is a mud which covers deposits in the old stream bed as well as the flood plain.

**Method of correlation.** The initial step in correlation is the construction of an isometric diagram showing all holes drilled. With such a diagram it is



easier to trace time equivalents because all plotted holes are in their proper spatial relationships. With drill logs plotted, the sandstones and mudstones are correlated (Fig. 17.1). Where a sandstone or a mudstone cannot be correlated from one hole to the next, but adjacent beds do correlate, it is shown as pinching out. After all units are correlated, the top of the first dominant and persistent mudstone below the potentially ore-bearing sandstone is selected as the base of the depositional unit, and the top of the first persistent mudstone above this sandstone is selected as the top of the unit.

When a depositional unit has been established, it is possible to construct subsurface maps of the various lithologic characteristics of the unit. The accuracy of any map is dependent upon the relationship between the persistency of the characteristic mapped and the density of control. Many types of subsurface maps are possible where hole density is sufficient, but for reconnaissance type drilling with widely spaced holes, only features of considerable magnitude and persistence can be mapped.

**Subsurface maps.** A lithofacies map employing the ratio of mudstone to sandstone content of the depositional unit was found to be the most diagnostic where holes are spaced 500 to 1000 feet apart (Fig. 17.2). The ratio-type map is preferred over a sandstone isopach or percentage map. The use of a relatively small contour interval served best to define areas of facies change and to force careful interpretation. After contouring, the choice of area to be shaded was based on a geometric interval to outline zones of significant differences.

Elongate patterns representing similar mudstone-sandstone facies not only indicate the trend of deposition, which can be projected for at least 1000 feet along the trend, but also present a close approximation of distribution of environments represented by the facies.

**Hypothesis concerning favorable ground.** Criteria for recognition of favorable ground, other than by mineralization itself, have long been a subject of conjecture. It is believed that the ore deposits as found today are localized in zones of change. The single effective change or combination of changes is unproven. This could be tectonic or sedimentary structure, wall-rock chemistry, physical properties of the host rock, some unknown change, or combinations of these.

The mudstone-sandstone lithofacies map of a depositional unit of the Salt Wash in the Cottonwood area indicates the position of a significant facies change by an increase in density of contours (Fig. 17.2). The interface between a dominantly sandy section and a dominantly muddy section is interpreted as the interface of change for many physical phenomena such as porosity, permeability, and resulting transmissivity. At this interface there is also variation in mineral content and chemical composition such as abun-



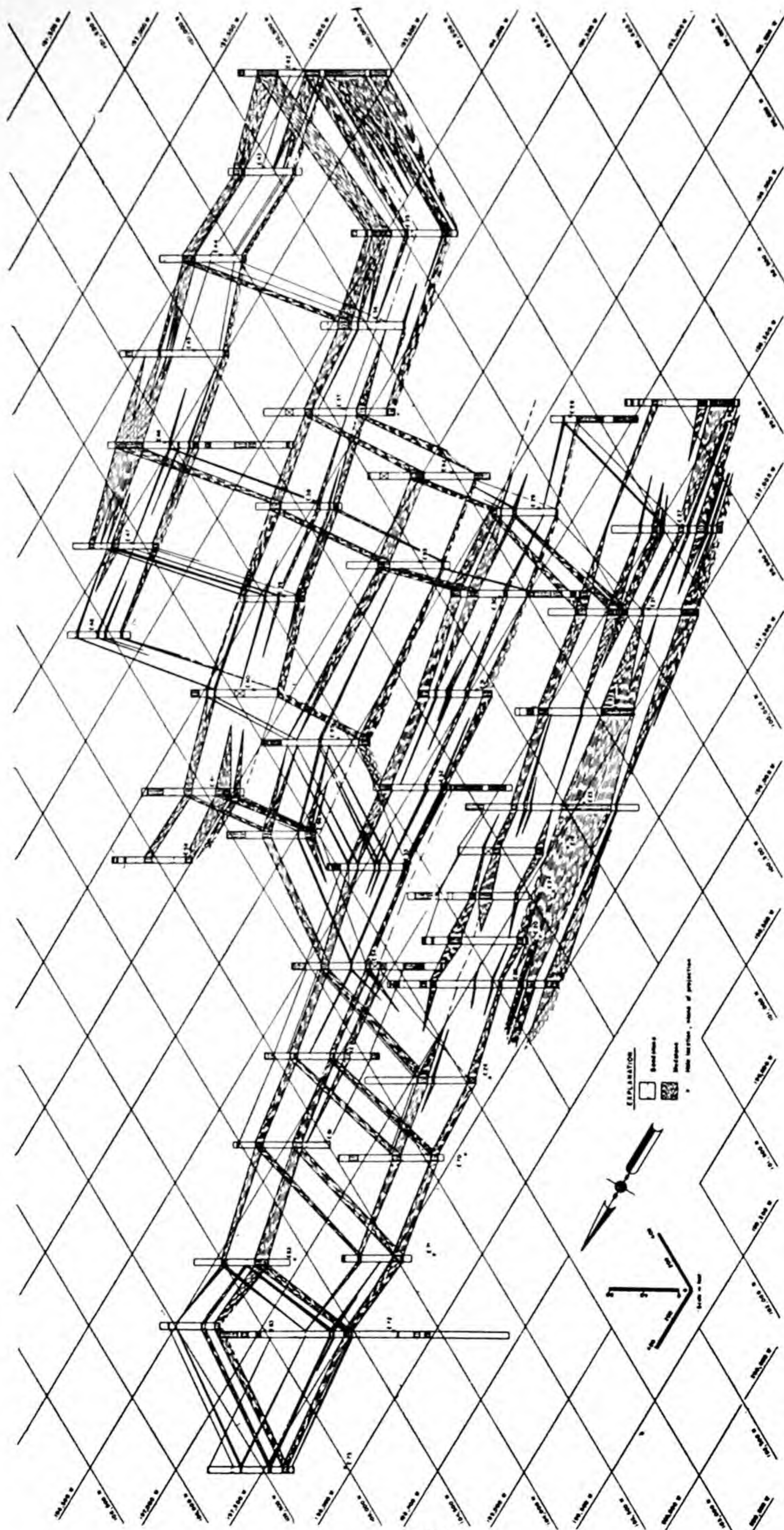
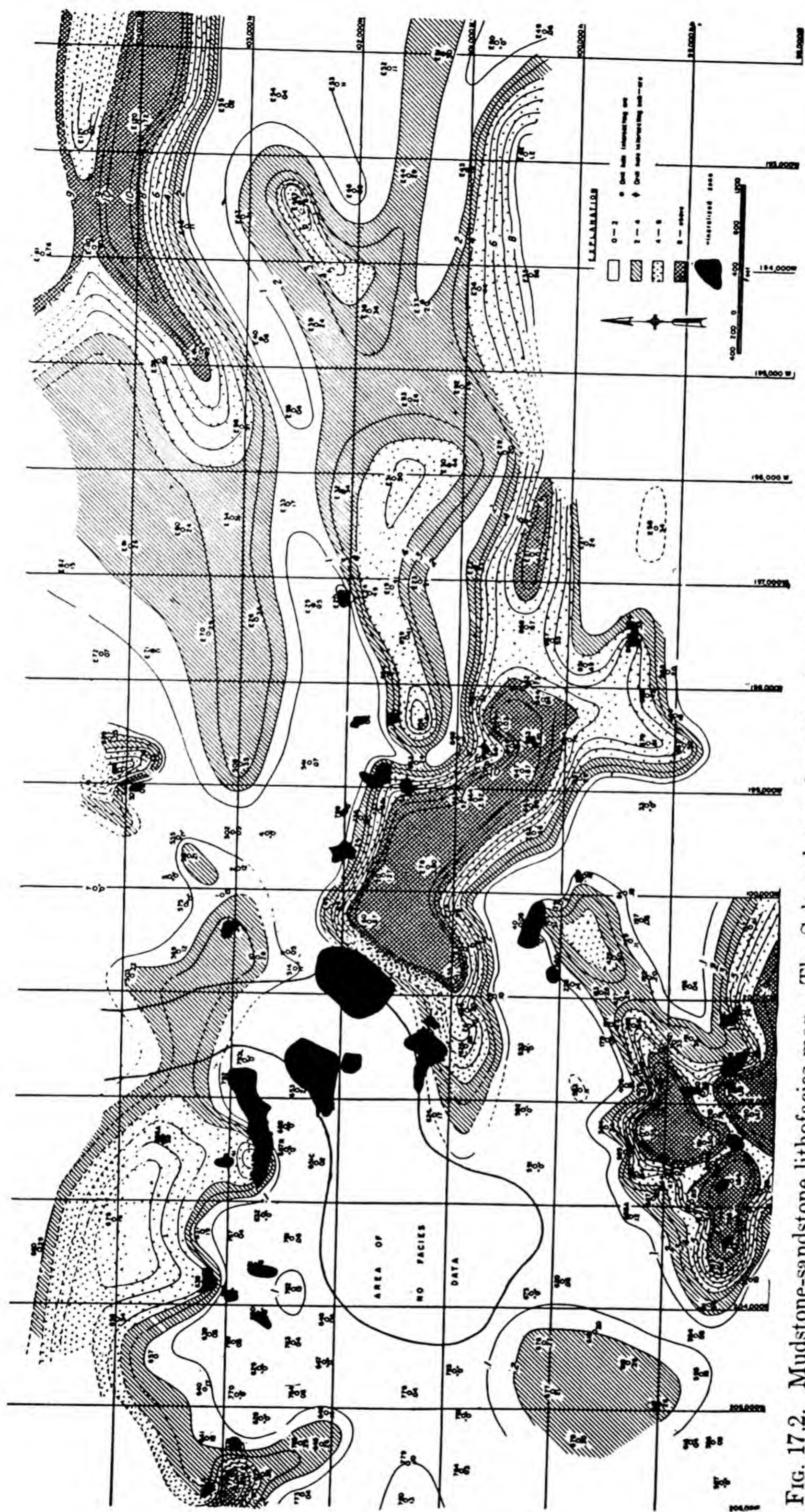


FIG. 17.1. Isometric correlation diagram. A portion of the Saltwash member, Morrison formation, Cottonwood Wash, San Juan County, Utah.







dance of carbon and variation in iron and sulfide content with all the related changes in  $E_H$  \* and pH.

Several worthy attempts have been made to statistically relate the ore deposits in the Salt Wash to a favorable thickness of host sandstone. The values determined by such studies are presumably correct for the area investigated but do not numerically agree. It is possible that all the thicknesses designated as favorable in each area may represent a similar environment between the fast and slow water sedimentation for that particular area. The same may be true for other features found to be statistically favorable in some localities but not in others.

In the mudstone-sandstone lithofacies map more than random coincidence is displayed between the location of mineral deposits and the position of facies or environment change (Fig. 17.2). This empirically derived evidence indicates that the interface area between the clean sandstone and the mudstone is the most favorable for ore accumulation. Such interfaces can be located by using data from widely spaced drill holes. Better maps, outlining more types of change, can be drawn when density of control is increased by closer spacing of drill holes.

To emphasize the areas of rapid facies change, a map may be constructed by placing tracing paper over the lithofacies map. A circle of arbitrary radius is inscribed on acetate, and a hole punched in the center. By placing a pencil in the center hole of the circle and placing the circle on the overlay it is possible to draw a line while moving the circle in such a manner that the same number of contours always appear within the circle. This system can be used to circumscribe the area of equal rate of change. It can be seen by superimposing the outline of mineral deposits on the resulting rate of change map that a good correlation exists (Fig. 17.3).

#### DRILLING PATTERNS FOR (SHINARUMP) PALEOCHANNELS †

Delineation of a paleochannel should begin with a row (fence) of holes a short distance behind the outcrop and across the projected trend to determine the channel axis by an alignment of the lowest point on the rim with the lowest point as interpreted from drill holes. Single holes, spaced no wider than the width of the channel, are then drilled on the axis projection. Immediately after completion of each hole, the elevation of the basal Shinarump contact is corrected for the effect of dip, the inferred contours are extended, and succeeding holes are located.

\* Oxidation potential. [Ed.]

† From Geneva Conference Paper 517, "Techniques and Guides for Exploration of Shinarump Channels on the Colorado Plateau" by H. B. Wood and W. D. Grundy, U.S. Atomic Energy Commission.



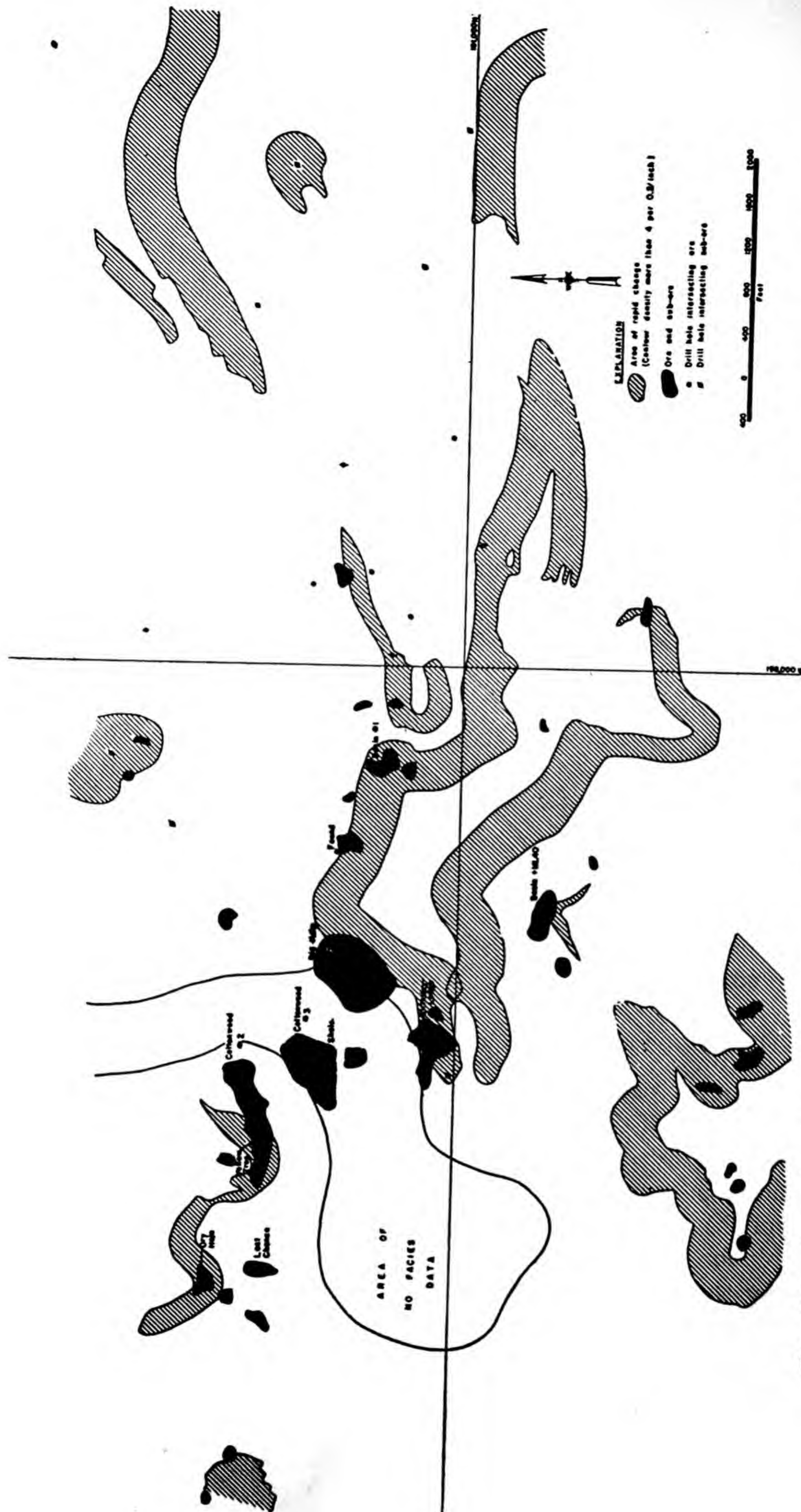


FIG. 17.3. Area of rapid change, mudstone-sandstone lithofacies. Cottonwood Wash, San Juan County, Utah.



If the last hole along a projected axis finds the basal Shinarump contact at a much higher corrected elevation than predicted from the extended contours, it may have been drilled either on a flank near a change in channel trend or on a rise in the channel floor. The uncertainty of the interpretation is resolved by drilling a fence of at least three holes half-way between the last two holes and at right angles to the last known channel trend. If the results of any fence are inconclusive, the fence is extended on either end, or additional holes are drilled between the primary holes of the fence. Wherever the interpretation of subsurface data is questionable, fences should be drilled in preference to single holes.

In channels where ore most frequently occurs in troughs, the distance between single holes should not exceed the maximum size of anticipated ore bodies. In channels where ore occurs predominantly on flanks, it is necessary to test the flanks between fences with additional holes.

#### SELECTED REFERENCES FOR CHAPTER 17

- Craig, L. C., C. N. Holmes, and others, 1955: *Preliminary Report on the Stratigraphy of the Morrison and Related Formations of the Colorado Plateau Regions*. U.S. Geological Survey Bulletin 1009-E.
- Stokes, W. L., 1954: *Relation of Sedimentary Trends, Tectonic Features and Ore Deposits in the Blanding District, San Juan County, Utah*. U.S. Atomic Energy Commission RME-3093 (Part I).
- Weir, D. B., 1952: *Geologic Guides to Prospecting for Carnotite Deposits on the Colorado Plateau*. U.S. Geological Survey Bulletin 988-B.



# Chapter 18

---

## SUBSURFACE RADIOMETRIC TECHNIQUES\*

---

---

Subsurface radiometric techniques include gamma-ray and neutron logging of exploratory drill holes and measurement of the radon content of gases issuing from soils, springs, and drill holes. The Geiger counter is almost universally used in logging small-diameter drill holes. The scintillation counter and the ionization chamber are widely used where the hole diameter is sufficiently large. Most logging instruments are installed in heavy-duty trucks, but lightweight portable equipment has been developed for logging shallow holes in remote locations. Measurements of radon in gas samples are made with ionization-chamber equipment in mobile laboratories.

In exploration for radioactive raw materials, the gamma-ray log of small-diameter drill holes has provided highly valuable information. Gamma-ray logs are used for (a) correlating stratigraphic horizons, (b) preparing lithologic logs where core recovery is poor or lacking, (c) determining depth and thickness of ore-bearing horizons, and (d) estimating semiquantitatively the thickness and grade of radioactive ores. Most of these uses have long been well established in the petroleum industry. The significant advances in the application of gamma-ray logging to exploration for radioactive materials are the direct quantitative assaying of ore in place and the preparation of subsurface isoradioactivity contour maps to guide further exploration at depth. The gamma-ray logging technique has been applied semiquantitatively in exploration for uranium, thorium, uraniferous phosphates, and potash.

The development of highly sensitive scintillation logging instruments offers promise, both of distinguishing among uranium, thorium, and potassium by spectrometry in the drill hole and of improving the lithologic interpretation of the gamma-ray log. One continuing difficulty in semiquantitative application of gamma-ray logs is the wide range of radioactivity found, from less than 0.001% to more than 10.0%  $U_3O_8$ . Thus far, with one particular detector or

\* The first section of this chapter is from Geneva Paper 511, "Instruments and Techniques for Measuring Radioactivity in the Field" by F. W. Stead, U.S. Geological Survey. Selected references are listed at the end of the chapter.



in a single logging operation, it has not been possible to obtain satisfactory measurements over this wide range of radioactivity.

Neutron logging techniques have been widely applied in the petroleum industry but have not been specifically developed to assist in exploration for radioactive materials. Measurement of the natural neutron flux in drill holes and neutron-gamma and neutron-neutron logging have been considered. As a practical exploration technique, neutron logging does not now seem promising as a direct aid in finding uranium and thorium ores. Combined gamma-ray and neutron logging has proved useful in estimating the grade and thickness of potash salts, and in distinguishing anhydrous from hydrous potash salts.

Migration of radon, a radioactive inert gas, offers a possible long-range method of detecting concealed radioactive materials. In gamma-ray logging of exploratory drill holes on the Colorado Plateau, small sharp anomalies detected several hundred feet downdip from carnotite ores are presumably caused by radon migrating in ground waters along permeable channels. Radon concentration in helium-bearing natural gases is being investigated, both to determine whether abnormally high radon concentration might indicate significant localized concentrations of uranium and radon at depth, and to clarify the relationship between radon and helium. Extremely high and variable concentrations of radon are occasionally found in mine openings and in drill holes penetrating uranium ore; in rare cases as much as  $1 \times 10^{-6}$  curies of radon per liter (STP) has been found. No clear-cut relationship has been established between the radon concentration in mine openings and drill holes and the uranium content of the country rock. Qualitatively, a high concentration of radon is suggestive of possibly significant uranium concentration nearby, but no quantitative conclusions can be drawn based on the radon content of gas samples from drill holes and mine openings.

#### SCINTILLATION DRILL-HOLE LOGGING \*

In the search for uranium on the Colorado Plateau, the U.S. Atomic Energy Commission designed a scintillation drill-hole logging unit, TU-5-A,† which has been utilized, with modifications, since 1952.

This unit includes a probe, a ratemeter, an audio power supply and a strip chart recorder (Figs. 18.1, 18.2).

**Subsurface unit.** The probe housing is a stainless-steel waterproof shell of approximately 29 inches length and  $2\frac{1}{16}$  inches outside diameter, the latter

\* From Geneva Conference Paper 512, "Scintillation Drill-Hole Logging" by S. S. Comstock, U.S. Atomic Energy Commission.

† H. J. Di Giovanni, R. T. Graveson, and A. H. Yoli, 1953: Scintillation unit for drill-hole logging. *Nucleonics* 11(4):34-39.





FIG. 18.1. Scintillation drill-hole logging unit.

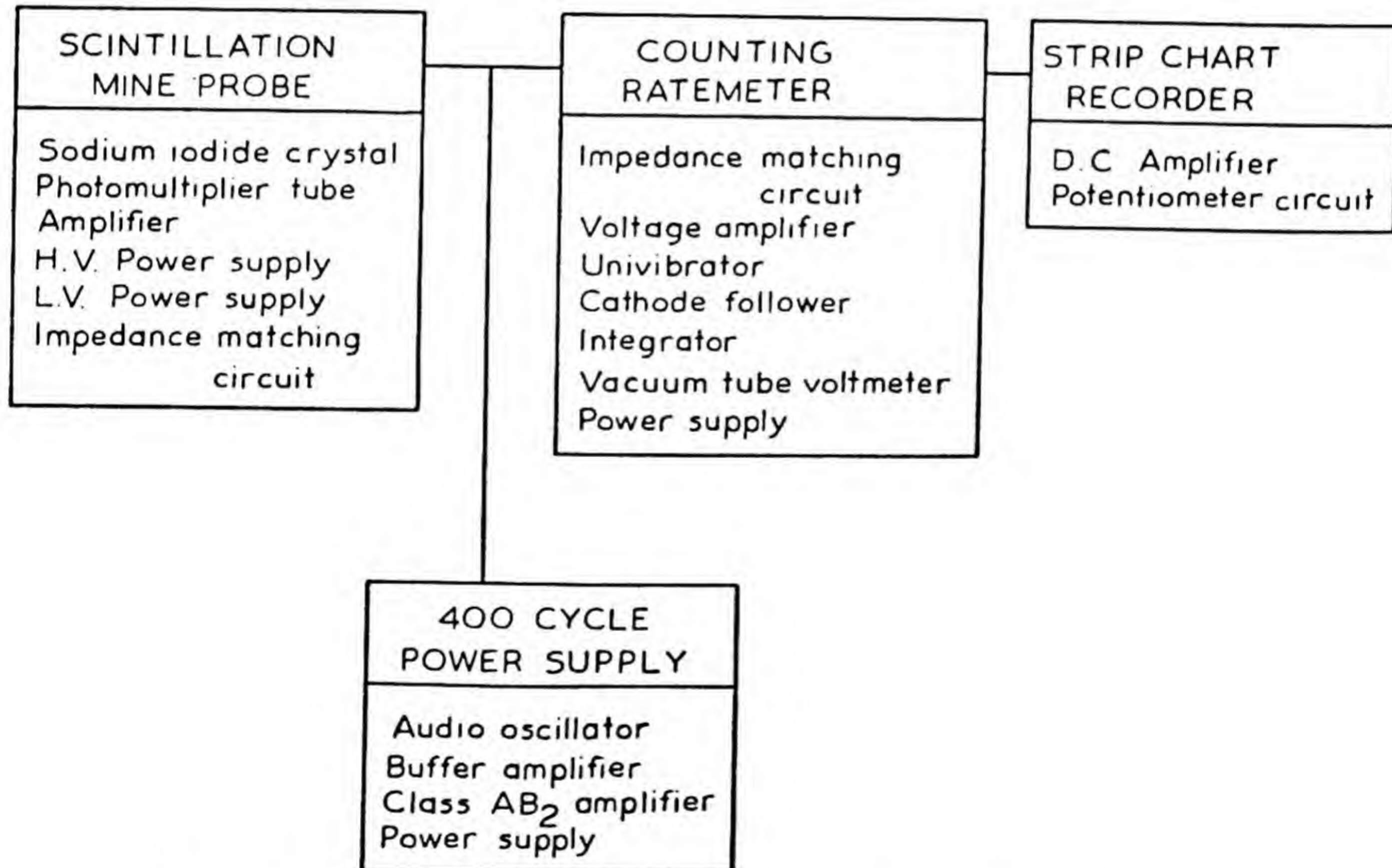


FIG. 18.2. Block diagram of scintillation drill-hole logging unit.



determined by that of a suitable photomultiplier tube. Mild-steel shells are unsatisfactory because they tend to become magnetized.

A gain in radial sensitivity over head-on sensitivity of 4 to 1 is achieved by a solid stainless-steel nose 3 inches long at the end of the probe. A single-conductor double-armored cable 1000 to 1600 feet long connects the probe to the surface unit.

The detector is a hermetically sealed, thallium-activated sodium iodide crystal,  $1\frac{1}{8}$  by  $1\frac{1}{2}$  inches, packed with an MgO reflector. The crystal is optically coupled to an RCA 6199 photomultiplier using black plastic to exclude light. The effect of magnetic fields is reduced by a mu-metal shield over the tube.

Impulses from the photomultiplier tube are fed to an amplifier which supplies pulses of adequate voltage to a ratemeter adjusted for a minimum detectable energy level of 30 kev. A B-voltage supply provides 200 volts to the amplifier stages from a primary source of 60 volts at 400 cycles. A regulated supply of 1000 volts from a primary source of 60 volts at 400 cycles is provided for the dynodes of the photomultiplier tube. Tube heaters are in series and supplied by a transformer output of 31.6 volts from an input of 60 volts at 400 cycles.

**Surface unit.** Signals pass from the cable, through an impedance-matching and frequency-discriminating unit, to a diode pulse clipper which cuts off the overshoot pulse formed by the impedance-matching transformer. Following the clipping circuit, pulses are fed to a voltage amplifier with a step control of the grid bias, which allows a selection of pulse sizes to be fed to the amplifier and acts as a pulse-height discriminator.

The voltage amplifier is followed by a conventional univibrator, adjusted to trip at 0.75 volt. "Dead time" is about 40 microseconds; this is the limiting factor in measuring linearly counting rates in excess of 10,000 counts per second. The univibrator feeds an integrating circuit through a cathode follower stage. Time constants in the integration circuit are controlled by varying the value of the integrating resistor.

Voltage from the integrating circuit is fed to a stable vacuum-tube voltmeter designed to provide 10 millivolts across a voltage dropping resistor. This provides drive to a 10 millivolt potentiometer-type recorder.

Full scale ranges of 10, 30, 100, 300, 1000, 3000, and 10,000 counts per second are provided. Time constants are  $\frac{1}{2}$ , 1, 2, 4, 8, and 16 seconds for logging at rates from 5 to 60 feet per minute.

Twelve watts of 400-cycle power are provided from an audio oscillator, a buffer, and a class AB<sub>2</sub> output stage for the probe power supply.

**Mechanical equipment.** A 3-kva 120/240-volt 60-cycle generator mounted at the front of the vehicle and driven by a power takeoff from the vehicle transmission is the source of primary power (Fig. 18.1). Vehicle engine speed



is controlled by a governor and either a mechanical or electrical throttle adjustment. By more recent modification, the generator is mounted inside the vehicle directly over the transmission.

The steel cable is wound on a winch driven by a D.C. motor which will lift the probe at speeds up to about 65 feet per minute. Servomechanisms drive the odometer and recorder-chart drive. The transmitting servomechanism is driven by a measuring wheel.

An underload switch cuts off the winch power when the probe contacts the bottom of the hole or an obstruction, and an overload switch performs the same function when the probe is stuck while raising. These safety switches may be bypassed by a remote-control switching unit if desired.

**Application.** Objectives in the utilization of gamma-ray logs are to obtain geologic data and to define, for ore-reserve calculations, mineralization in terms of thickness and grade.

The extent to which geology may be interpreted from a gamma-ray log must be determined anew for each area by careful comparison of the core and the gamma-ray log of the same hole. Study of core reveals the thickness of sandstone, presence of gray, red, and brown mudstone, mudstone flakes in sandstone, and similar features which are of aid in exploration drilling. From a gamma-ray record, a generalized lithologic log may be constructed in drilling areas where core recovery is poor or where no coring is done. Isoradioactivity maps, correlation of intraformational units, construction of stratigraphic sec-

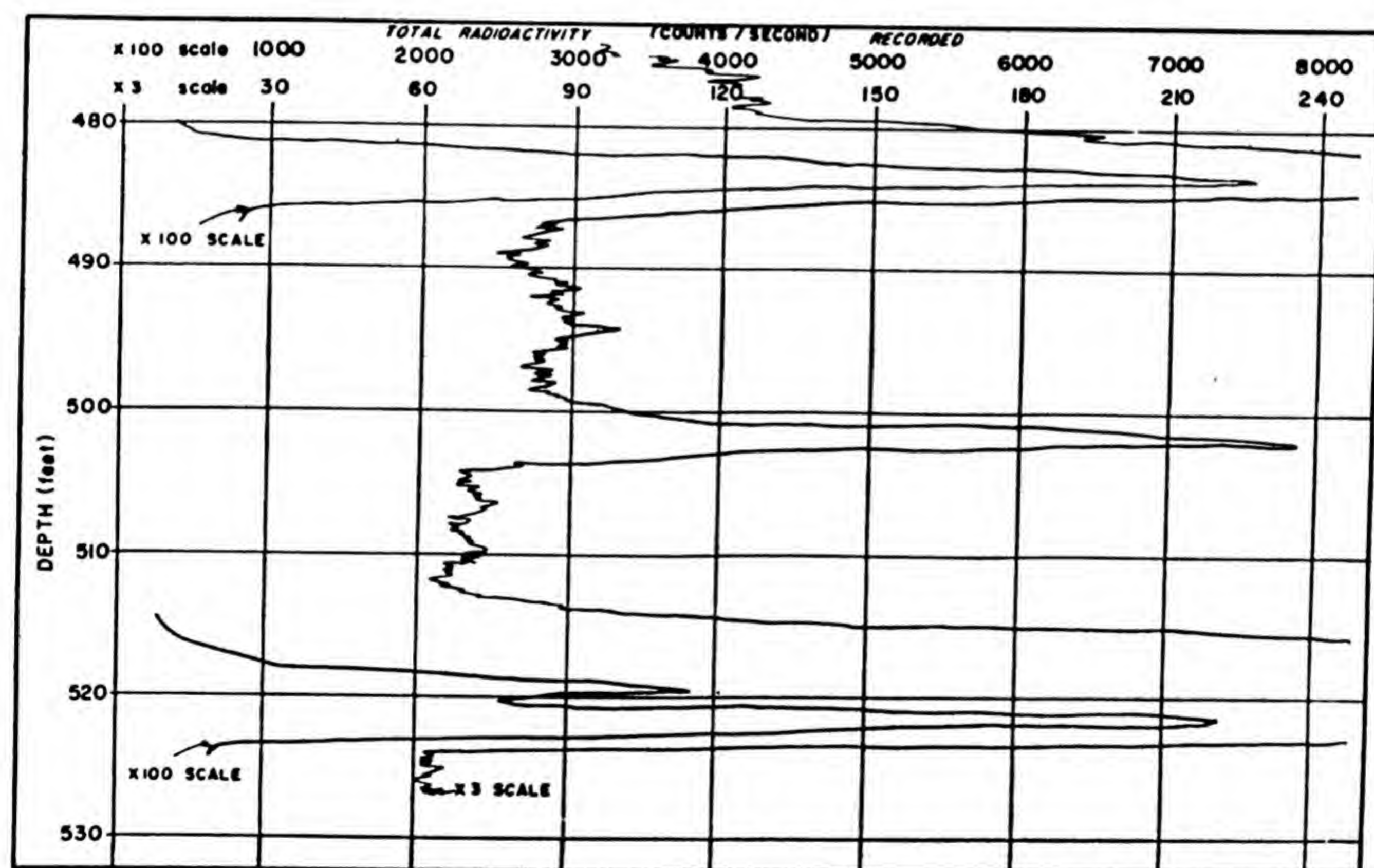


FIG. 18.3. Gamma-ray log of ore zone.



tions and panel diagrams, structure contour maps, isopach and mudstone-sandstone ratio maps are being used in exploratory drilling, and data for their preparation may be interpreted from radioactivity logs (Fig. 18.4). In specific search for ore bodies, it is essential to know the relative assay of an ore horizon penetrated in order to locate immediately an offset drill hole. Such information, in terms of equivalent percent of  $U_3O_8$ , may be had immediately by a properly calibrated instrument.

Calibration for assay purposes is achieved by use of a standard horizontal test hole which consists of circular sections 36 inches in diameter and 1 foot, 2 feet, and 3 feet in length (Fig. 18.5). Sections are filled with crushed mineralized rock of known  $U_3O_8$  content, or barren sand. Sections can be interchanged by the use of a hoist.

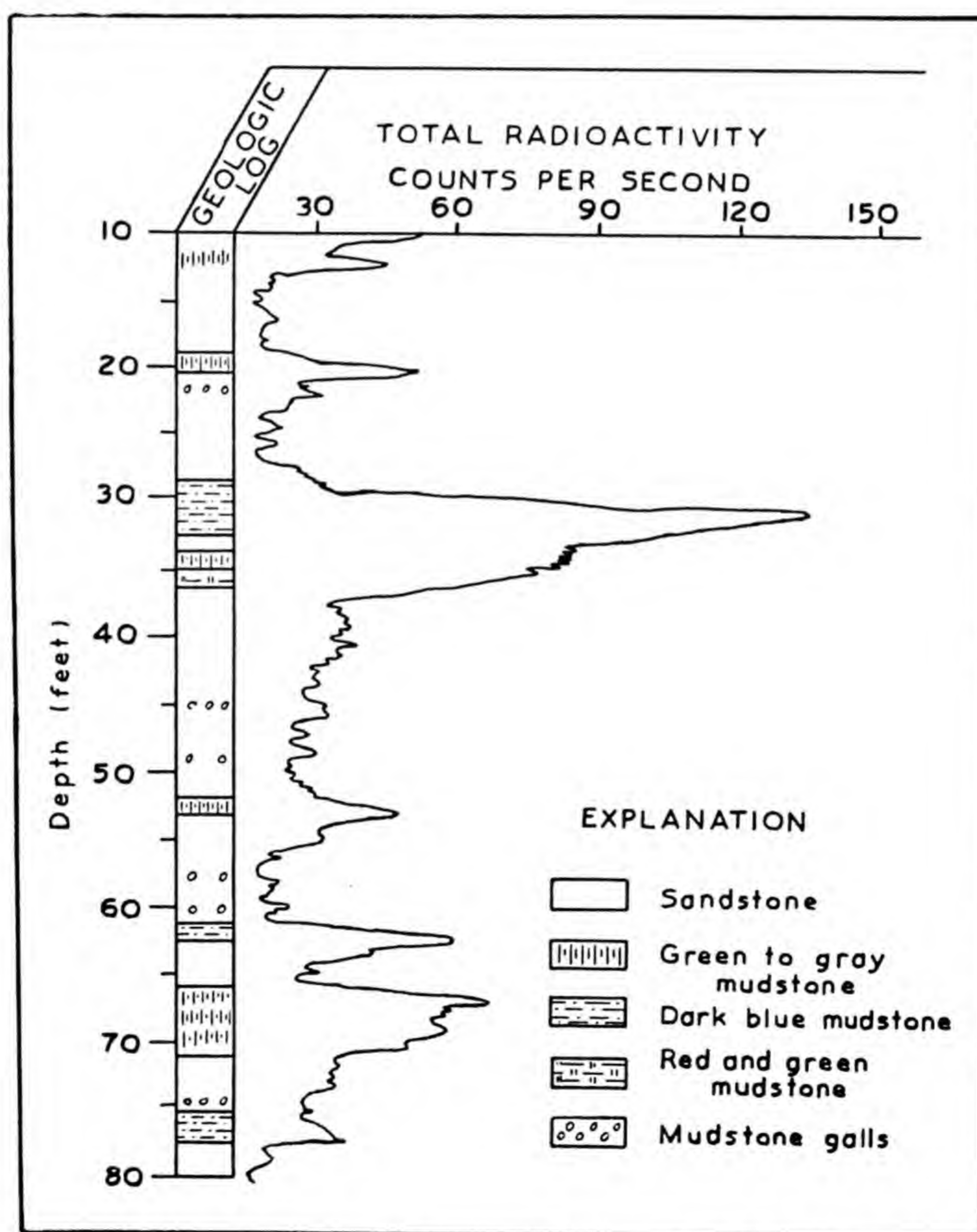


FIG. 18.4. Lithologic interpretation with gamma-ray log.



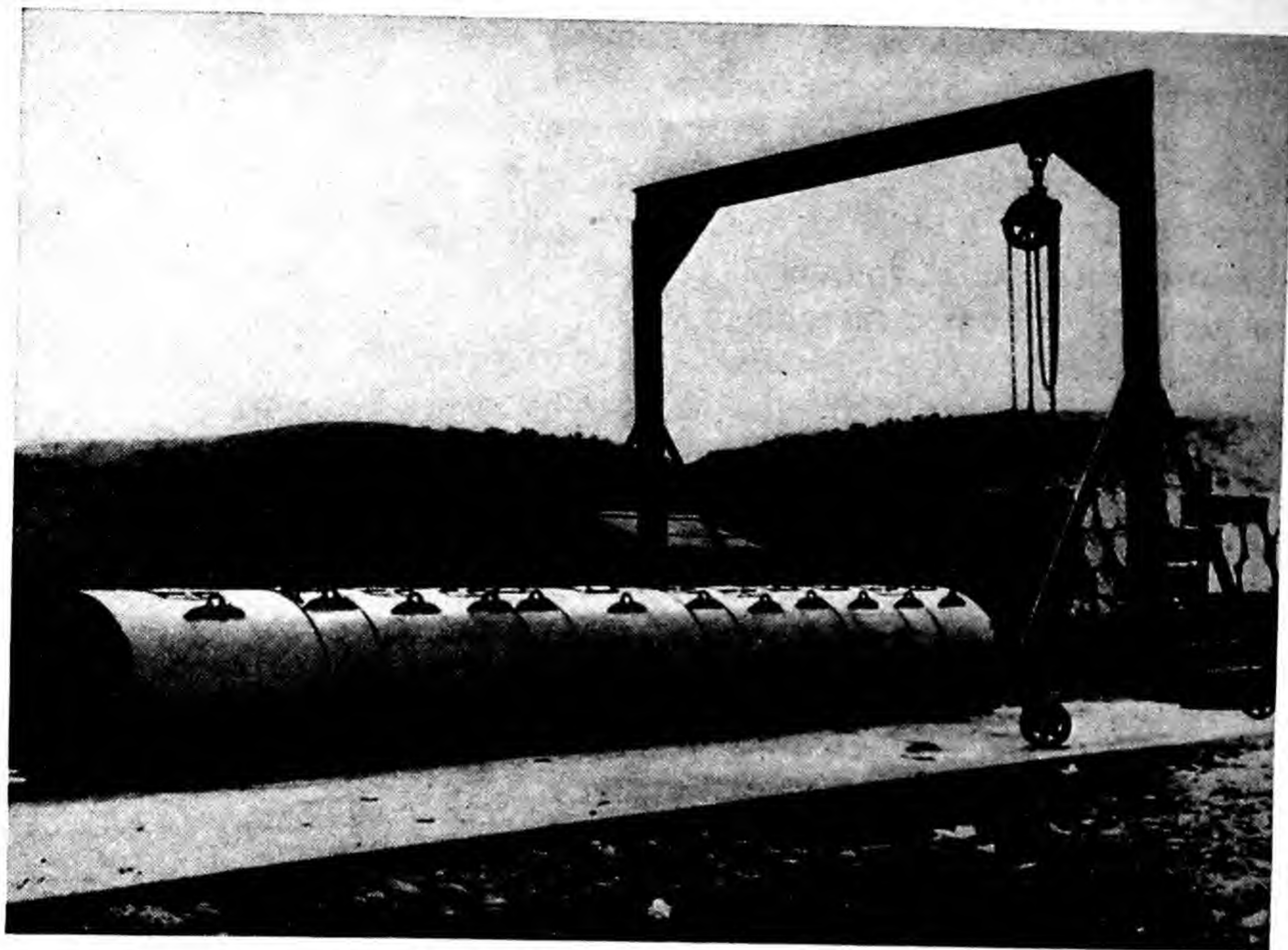


FIG. 18.5. Assay calibration test hole.

Figure 18.6 illustrates the performance characteristics of the TU-5-4 logging unit which are fundamental in radiometric log assaying. For a given grade of ore, the count rate is proportional to thickness of ore up to 3 feet.

#### SELECTED REFERENCES FOR CHAPTER 18

- Di Giovanni, H. J., R. T. Graveson, and A. H. Yoli, 1953: Scintillation unit for drill-hole logging. *Nucleonics* 11(4):34-39.
- Faul, Henry, 1954: Nuclear logging of drill holes for mineral exploration and soil studies. In H. Faul (Ed.), *Nuclear Geology*, New York, John Wiley & Sons, Inc., pp. 250-255.
- Tittle, C. W., 1954: Gamma-ray and neutron logging in the petroleum industry. In H. Faul (Ed.), *Nuclear Geology*, New York, John Wiley & Sons, Inc., pp. 241-250.



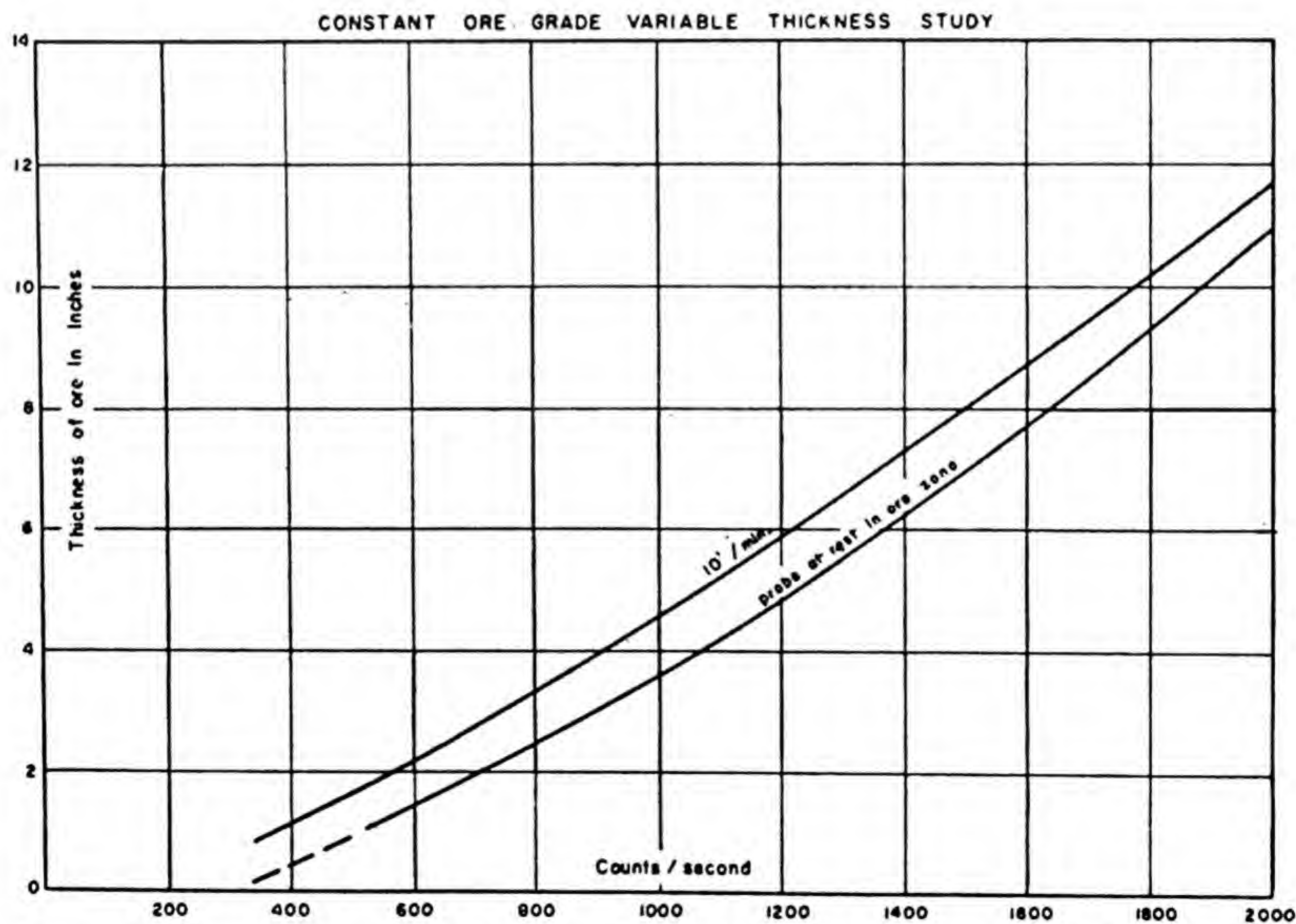
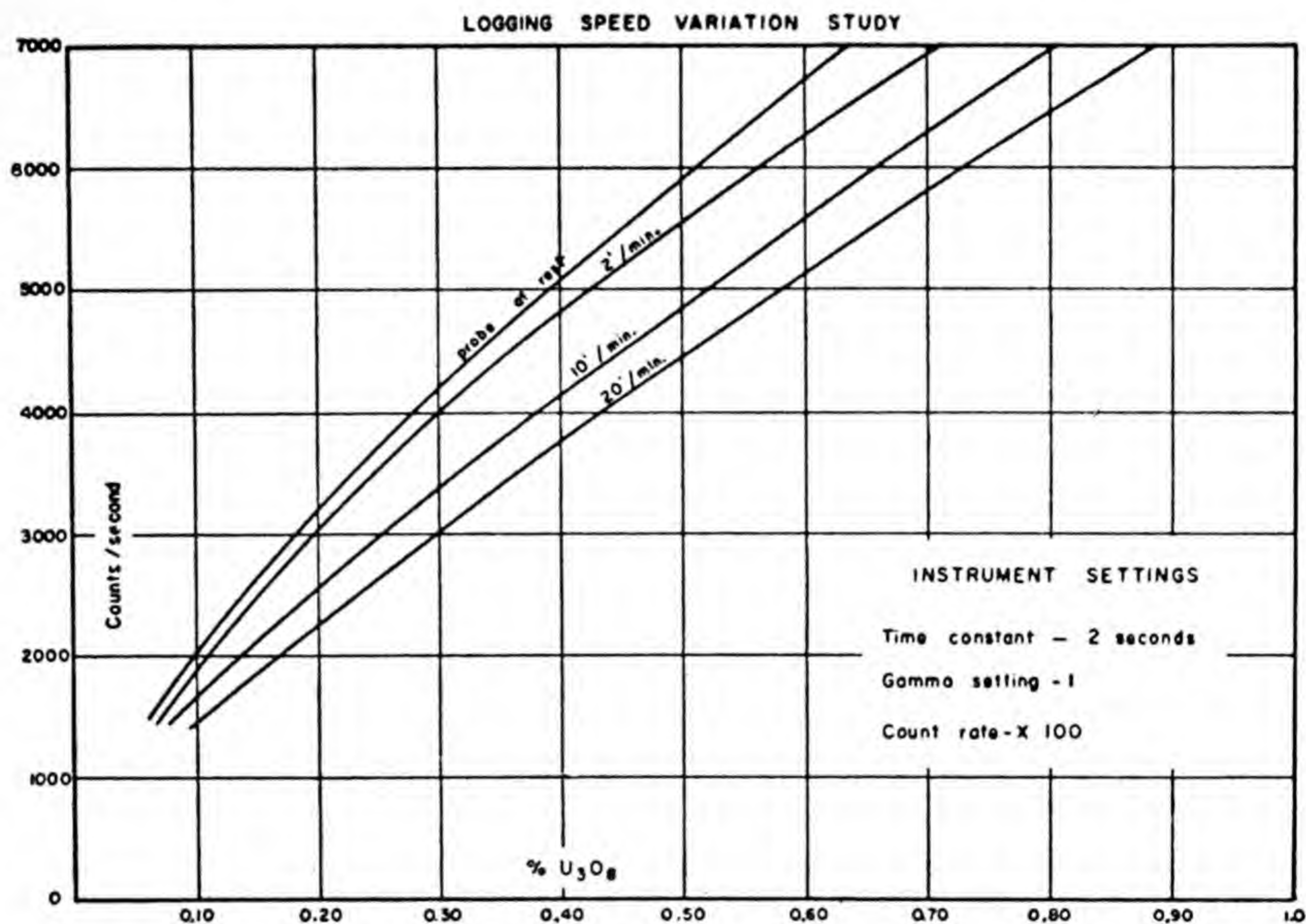


FIG. 18.6. Performance characteristics for TU-5-A logging unit. (Data from horizontal test hole.)



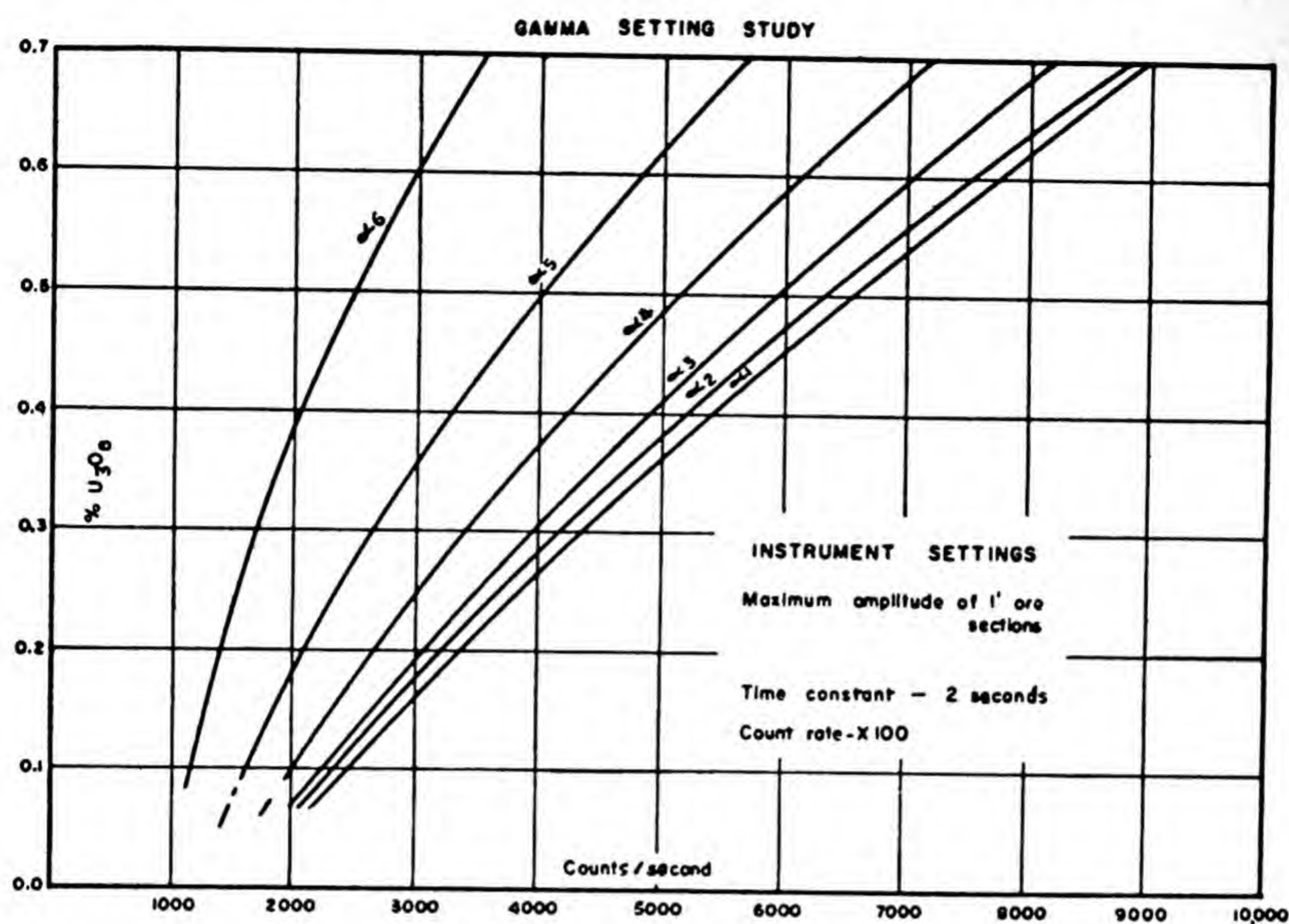


FIG. 18.6. (Continued.)



# GENEVA CONFERENCE PAPERS ON THE NATURAL OCCURRENCE OF URANIUM AND THORIUM

<i>Paper Number</i>	<i>Author and Title</i>	<i>Country</i>
14	M. R. Klepper and D. G. Wyant. Uranium provinces.	U.S.A.
15	A. P. Butler and R. W. Schnabel. Distribution of uranium occurrences in the United States.	U.S.A.
16	G. J. Neuerburg. Uranium in igneous rocks of the United States of America.	U.S.A.
17	E. S. Larsen, Jr., G. Phair, D. Gottfried, and W. L. Smith. Uranium in magmatic differentiation.	U.S.A.
18	R. R. Coats. Distribution of uranium and certain other trace elements in felsic volcanic rocks of Cenozoic age of the western United States.	U.S.A.
19	B. J. Sharp. Uranium deposits in volcanic rocks of the basin and range province.	U.S.A.
20	D. L. Everhart. Uranium-bearing vein deposits in the United States.	U.S.A.
21	P. K. Sims and E. W. Tooker. Pitchblende deposits in the Central City district and adjoining areas.	U.S.A.
22	G. E. Becraft. Uranium deposits of the Boulder Batholith, Montana.	U.S.A.
23	M. H. Staatz and F. W. Osterwald. Uranium in the fluorspar deposits of the Thomas Range, Utah.	U.S.A.
24	J. W. Adams and F. Stugard, Jr. Wall-rock control of certain pitchblende deposits in Golden Gate Canyon, Jefferson County, Colorado.	U.S.A.
25	G. W. Walker and F. W. Osterwald. Relation of secondary uranium minerals to pitchblende-bearing veins at Marysvale, Piute County, Utah.	U.S.A.
27	E. R. Thurlow. Uranium deposits at the contact of meta-sediments and granitic intrusives in the western United States.	U.S.A.
28	F. W. Osterwald. Relation of tectonic elements in pre-Cambrian rocks to uranium deposits in the Cordilleran foreland of the western United States.	U.S.A.
29	V. C. Kelley. Influence of regional structure upon the origin and distribution of uranium on the Colorado Plateau.	U.S.A.
30	H. B. Wood. Age and environment of uranium host rocks in the United States.	U.S.A.
32	D. A. Jobin. Regional transmissivity of the exposed sediments of the Colorado Plateau as related to the distribution of uranium deposits.	U.S.A.
33	D. A. Phoenix. Relation of carnotite deposits to permeable rocks in the Morrison formation, Mesa County, Colorado.	U.S.A.
34	F. G. Poole and G. A. Williams. Direction of transportation of the sediment constituting the Triassic and associated formations of the Colorado Plateau.	U.S.A.
35	R. L. Boardman, E. B. Ekren, and H. E. Bowers. Sedimentary features of upper sandstone lenses of the Salt Wash	



<i>Paper Number</i>	<i>Author and Title</i>	<i>Country</i>
	sandstone member and their relation to uranium-vanadium deposits in the Uravan District, Montrose County, Colorado.	U.S.A.
36	D. R. Shawe. Significance of roll ore bodies in genesis of uranium-vanadium deposits on the Colorado Plateau.	U.S.A.
37	J. W. Gabelman. Uranium deposits in limestone.	U.S.A.
38	L. S. Hilpert and V. L. Freeman. Guides to uranium deposits in the Gallup-Laguna area, New Mexico.	U.S.A.
39	Y. W. Isachsen. Geology of uranium deposits of the Shinarump and Chinle formations on the Colorado Plateau.	U.S.A.
40	I. J. Witkind. Channels and related swales at the base of the Shinarump conglomerate, Monument Valley, Arizona.	U.S.A.
41	W. S. Keys. Deep drilling in the Temple Mountain collapse, San Rafael Swell, Utah.	U.S.A.
42	A. F. Trites, Jr., T. L. Finnell, and R. E. Thaden. Uranium deposits in the White Canyon area, San Juan County, Utah.	U.S.A.
43	L. W. Carithers. Uranium in shoreline sandstones of terrestrial and marine origin, Colorado Plateau.	U.S.A.
44	D. L. Davis and D. L. Hetland. Uranium in clastic rocks of the Basin and Range Province.	U.S.A.
45	E. W. Grutt. Uranium deposits in Tertiary clastics in Wyoming and Northern Colorado.	U.S.A.
46	W. N. Sharp, F. A. McKeown, E. J. McKay, and A. M. White. Geology and uranium deposits of the Pumpkin Buttes area, Powder River Basin, Wyoming.	U.S.A.
47	H. Bell, III, G. B. Gott, E. V. Post, R. W. Schnabel, and others. Lithologic, structural and geochemical controls of uranium deposition in the Southern Black Hills, South Dakota.	U.S.A.
48	E. M. Shoemaker. Occurrence of uranium in diatremes on the Navajo-Hopi Reservations, Arizona, New Mexico and Utah.	U.S.A.
49	I. A. Breger and M. Deul. The organic geochemistry of uranium.	U.S.A.
50	J. W. Gabelman. Uranium deposits in paludal black shales of the Dakota formation, San Juan Basin, New Mexico.	U.S.A.
51	V. E. Swanson. Uranium in marine black shales of the United States.	U.S.A.
52	L. C. Conant. Environment of accumulation of the Chattanooga shale.	U.S.A.
53	A. Brown. Uranium in the Chattanooga shale of eastern Tennessee.	U.S.A.
54	W. J. Mapel. Uraniferous black shales in the Northern Rocky Mountains and Great Plains regions.	U.S.A.
55	J. D. Vine. Uranium-bearing coal in the United States.	U.S.A.
56	H. Masursky. Trace elements in coal in the Red Desert, Wyoming.	U.S.A.
57	N. M. Denson and J. R. Gill. Uranium-bearing lignite and its relation to volcanic tuffs in eastern Montana and the Dakotas.	U.S.A.



<i>Paper Number</i>	<i>Author and Title</i>	<i>Country</i>
126	D. Guimaraes. The areas of geologically probable occurrences of uranium and thorium in Brazil.	Brazil
127	L. J. de Morais. Known occurrences of uranium and thorium in Brazil.	Brazil
128	O. H. Leonardos. Monazite in Brazil.	Brazil
129	L. J. de Morais, M. G. White, and G. E. Tolbert. The uraniferous zirconium ores of the Pocos de Caldas Plateau.	Brazil
130	M. G. White, E. Távora, and others. The occurrence of uranium associated with auriferous conglomerate in the Serra de Jacobina, Bahia, Brazil.	Brazil
131	D. Guimaraes and others. The stannio-tantalum-uraniferous deposits and occurrences in the region of S. João del Rei, Minas Gerais, Brazil.	Brazil
285	R. C. Derzay. The Los Ochos uranium deposit.	U.S.A.
286	J. W. King. High grade uraniferous lignites in Harding County, South Dakota.	U.S.A.
287	G. N. Pipiringos. Uranium-bearing coal in the central part of the Great Divide Basin, Sweetwater County, Wyoming.	U.S.A.
288	W. J. Hail, Jr., A. T. Myers, and A. C. Horr. Uranium in asphalt-bearing rocks.	U.S.A.
289	A. P. Pierce, J. W. Mytton, and G. B. Gott. Radioactive elements and their daughter products in the Texas Panhandle and other oil and gas fields in the United States.	U.S.A.
290	V. E. McKelvey. Uranium in phosphate rock.	U.S.A.
291	V. E. McKelvey and L. D. Carswell. Uranium in the Phosphoria formation.	U.S.A.
292	Z. S. Altschuler, E. B. Jaffe, F. Cuttitta, and others. The aluminum phosphate zone of the Bone Valley formation and its uranium deposits.	U.S.A.
293	J. B. Cathcart. Distribution and occurrence of uranium in the calcium phosphate zone of the land-pebble phosphate district of Florida.	U.S.A.
294	K. Bell. Uranium in precipitates and evaporites.	U.S.A.
295	A. D. Weeks. Mineralogy and oxidation of the Colorado Plateau uranium ores.	U.S.A.
296	J. W. Gruner. A comparison of black uranium ores in Utah, New Mexico and Wyoming.	U.S.A.
297	R. A. Laverty and E. B. Gross. Paragenetic studies of uranium deposits of the Colorado Plateau.	U.S.A.
298	L. R. Stieff and T. W. Stern. Interpretation of the $Pb^{206}/U^{238} < Pb^{207}/U^{235} \ll Pb^{207}/Pb^{206}$ age sequence of uranium ores.	U.S.A.
299	H. R. Hoekstra and J. J. Katz. The isotope geology of some uranium minerals.	U.S.A.
300	V. E. McKelvey, D. L. Everhart, and R. M. Garrels. Summary of hypotheses of genesis of uranium deposits.	U.S.A.
301	W. S. Twenhofel and K. L. Buck. The geology of thorium deposits in the United States.	U.S.A.
302	C. Frondel. The mineralogy of thorium.	U.S.A.
303	Q. D. Singewald and M. R. Brock. Thorium deposits in the Wet Mountains, Colorado.	U.S.A.



<i>Paper Number</i>	<i>Author and Title</i>	<i>Country</i>
304	S. R. Wallace and J. C. Olson. Thorium in the Powderhorn District, Gunnison County, Colorado.	U.S.A.
305	J. H. Mackin and D. L. Schmidt. Uranium- and thorium-bearing minerals in placer deposits in Idaho.	U.S.A.
306	W. C. Overstreet, N. P. Cuppels, and A. M. White. Monazite in the southeastern United States.	U.S.A.
307	R. C. Vickers. Geology and monazite content of the Goodrich quartzite, Palmer area, Marquette County, Michigan.	U.S.A.
328	M. Roubault. Les gisements d'uranium de la France métropolitaine et des territoires français d'outre-mer.	France
470	J. C. Johnson. Nuclear fuel for the World Power program.	U.S.A.
471	Staffs of U.S. Geological Survey and U.S. Atomic Energy Commission. Natural occurrence of uranium in the United States.	U.S.A.
472	W. I. Finch. Uranium in terrestrial sedimentary rocks in the United States exclusive of the Colorado Plateau.	U.S.A.
473	R. P. Fischer. Uranium-vanadium-copper deposits of the Colorado Plateau region.	U.S.A.
474	P. H. Dodd. Some examples of uranium deposits in the upper Jurassic Morrison formation on the Colorado Plateau.	U.S.A.
759	C. F. Davidson. The radioactive mineral resources of Great Britain.	U.K.
760	C. F. Davidson. Radioactive minerals in the Central African Federation.	U.K.
761	C. F. Davidson. Radioactive minerals in the British Colonies.	U.K.
782	E. Svenke. The occurrence of uranium and thorium in Sweden.	Sweden
850	H. Brown and L. T. Silver. The possibilities of securing long-range supplies of uranium, thorium and other substances from igneous rocks.	U.S.A.
865	J. T. Shen. Exploration of monazite and associated minerals in the province of Taiwan, China.	China
875	D. N. Wadia. Natural occurrences of uranium and thorium in India.	India
887	T. Siggerud. Occurrence of uranium and thorium in Norway.	Norway
918	F. Ippolito. Present state of uranium surveys in Italy.	Italy
956	Survey paper on the natural occurrences of uranium and thorium in Thailand.	Thailand
963	M. Ristić. Deposits of uranium and thorium in Yugoslavia.	Yugoslavia
968	R. Cavaca. Uranium prospection in Portugal.	Portugal
980	A. Clemente and E. Reyes. Uranium deposits in the Philippines.	Philippines
1000	E. Linares. El yacimiento Eva Perón, Malargue, Mendoza.	Argentina
1001	A. Belluco. Las vetas de cuarzo uranífero del yacimiento Presidente Perón, Mendoza.	Argentina
1035	P. Huber. Uranium prospection in Switzerland.	Switzerland
1036	Ministry of International Trade and Industry. Natural occurrence of uranium and thorium in Japan.	Japan
1071	Commonwealth Department of National Development. Natural occurrence of U and Th.	Australia
1114	P. F. Kerr. The Natural Occurrence of Uranium and Thorium.	U.N.



# GENEVA CONFERENCE PAPERS ON PROSPECTING FOR URANIUM AND THORIUM

<i>Paper Number</i>	<i>Author and Title</i>	<i>Country</i>
1	A. H. Lang. Uranium prospecting in Canada—aerial and ground surveys.	Canada
132	D. A. MacFadyen and S. V. Guedes. Air survey applied to the search for radioactive minerals in Brazil.	Brazil
338	A. Lenoble. Méthode de recherches et d'étude des gîtes uranifères.	France
502	P. F. Kerr. Rock alteration criteria in the search for uranium.	U.S.A.
503	Staffs, U.S. Atomic Energy Commission and U.S. Geological Survey. Techniques of prospecting for uranium and thorium.	U.S.A.
504	L. R. Page. Geologic prospecting for uranium and thorium.	U.S.A.
505	W. C. Overstreet, P. K. Theobald, Jr., <i>et al.</i> Heavy mineral prospecting.	U.S.A.
506	P. F. Fix. Geochemical prospecting for uranium by sampling ground and surface waters.	U.S.A.
507	N. M. Denson, H. D. Zeller, and J. G. Stephens. Water sampling as a guide in the search for uranium deposits and its use in evaluating widespread volcanic units as potential source beds for uranium.	U.S.A.
508	T. S. Lovering, F. C. Canney, H. W. Lakin, and F. N. Ward. The use of geochemical techniques and methods in prospecting for uranium.	U.S.A.
509	H. L. Cannon, F. J. Kleinhampl, <i>et al.</i> Botanical methods of prospecting for uranium.	U.S.A.
510	T. L. Boyle. Airborne radiometric surveying.	U.S.A.
511	F. W. Stead. Instruments and techniques for measuring radioactivity in the field.	U.S.A.
512	S. S. Comstock. Scintillation drill-hole logging.	U.S.A.
513	J. W. Chester. Drilling techniques in search of uranium.	U.S.A.
514	R. A. Black. Geophysical exploration for uranium on the Colorado Plateau.	U.S.A.
515	M. E. Denson, Jr. Geophysical-geochemical prospecting for uranium.	U.S.A.
516	R. K. Pitman, P. H. Dodd, and C. W. Tom. Subsurface techniques for outlining favorable zones using widely spaced core drilling.	U.S.A.
517	H. B. Wood and W. D. Grundy. Techniques and guides for exploration of Shinarump channels on the Colorado Plateau.	U.S.A.
518	A. F. Sakakura. Air scattering of gamma-rays from thick uranium sources.	U.S.A.
625	V. I. Baranov. Aeroradiometric prospecting for uranium and thorium deposits and the interpretation of gamma anomalies.	U.S.S.R.
626	A. A. Saukoff. Radiohydrogeological methods in prospecting for uranium deposits.	U.S.S.R.



<i>Paper Number</i>	<i>Author and Title</i>	<i>Country</i>
763	H. Bisby, E. Franklin, and D. Taylor. Instrumental developments in the prospecting, mining, and chemical processing of nuclear materials.	U.K.
764	C. F. Davidson and S. H. U. Bowie. Methods of prospecting for uranium and thorium.	U.K.
773	S. Amiel and L. Winsberg. Measurements on natural water sources as aid in prospecting, for underground deposits of uranium.	Israel
869	K. G. Vohra. Remote location of uranium and thorium deposits.	India
994	A. Milojevic, V. Kostic, and M. Petrovic. Radiation detectors with halogen counters for use in prospecting.	Yugoslavia



## SUBJECT INDEX

---

- Ace mine**, 26  
 Aerial radiometry, 155-92  
 Albite, 73  
 Alkali metal silicates, 73  
 Alkali metals, 9, 57, 72, 112  
 Allanite, 73, 114  
 Alluvium, 42  
 Alumina, 44  
 Aluminum, 9, 17, 78  
 Aluminum oxide, 76  
 Aluminum phosphate, 44, 54  
 Alunite, 119  
 Alunitization, 119  
 Amphibole, 109  
 Anorthosite, 24  
 Apatite, 44, 56, 68, 69, 73, 187  
 Argillite, 29, 78  
 Argillization, 117  
 Argon, 39, 43  
     isotopic abundance of, 232, 234  
 Arkose, 42, 78, 80, 113  
 Arsenic, 9, 42, 53, 112, 113, 116, 217, 254, 255  
 Asphalt, asphaltite, 38-40, 42, 43, 52, 59, 61, 113, 116, 120, 128  
 Assay, chemical, 153  
     fluorimetric, 153  
     radiometric, 153  
 Aster, 228  
 Autunite, 15-20, 29, 54, 63, 210, 248-9, 255  
  
**Barium**, 112  
 Basalt, 52, 79, 81, 108  
 Bastnaesite, 31  
 Becquerelite, 15  
 Bentonite, 42  
 Beryl, 112  
 Beryllium, 9, 24, 72  
 Betafite, 121  
 Betauranotile, 15  
 Bibliography, 277-282  
 Biotite, 57, 73, 112, 118, 124  
 Bismuth, 28, 46, 112  
 Bismuthinite, 133  
 Bitumen, bituminous deposits, 31, 39, 66, 244, 245  
 Blind River, 30  
 Borehole logging, *see* Logging  
 Boring machinery, 169  
 Bornite, 19, 116  
 Brannerite, 15, 16, 24, 58, 73, 76, 112, 121  
  
**Calcite**, 24, 25, 74, 210  
 Calcium, 9, 16, 18, 21, 22, 25, 47, 68-9, 112, 120, 204-5, 225, 228-9, 237, 254-5  
 Calcium carbonate, 25, 39, 109  
 Calcium fluoride, 25, 117  
 Calcium phosphate, 43, 44, 210  
 Calcium silicate, 24  
 Calibration of instruments, 141-143  
 Caliche, 119  
 Caliche-type mineralization, 103  
 Carbon, 19, 113, 265  
 Carbon dioxide, 58, 68, 110  
 Carbonaceous rocks, 247, 248  
 Carbonates, 44, 53, 57, 66, 68, 69, 113, 212  
 Carbonatites, 74  
 Carburan, 15, 43  
 Carnotite, 15-17, 20, 53-4, 71, 75, 104-5, 210, 225, 228, 248, 255, 260, 269  
 Cattierite, 27  
 Cerium metals, 44  
 Cerium oxide, 117  
 Chalcedony, 114, 132, 133  
 Chalcopyrite, 14, 19, 116, 133  
 Chamber, ionization, 102, 268  
 Charcoal, 65  
 Chert, 66, 77-8, 120  
 Chlorine, 204-5, 234, 237



- Chlorite, 59, 62, 115  
 Chloritization, 117  
 Chloritoid, 126  
 Chromium, 19  
 Circuit, scaling, 141  
 Clastic rocks, 52  
 Clay, 29, 44, 47, 62, 75, 103, 111, 113, 115, 117, 118, 128, 204  
 Claystone, 91, 128, 248  
 Coal, 2, 18, 19, 38-41, 52, 55, 63-65, 72, 74-5, 79, 80, 87, 91, 112, 113, 115, 226  
 Cobalt, 9, 19, 27-8, 57-8, 104, 112, 113, 217, 219, 223  
     determination of, 222  
 Cobalt arsenate, 129  
 Cobalt carbonate, 129  
 Cobalt sulfate, 129  
 Cobalt sulfide, 19, 27, 46  
 Coffinite, 17, 19, 43, 53-4, 59  
 Colorado Front Range, 210  
 Colorado Plateau, regional structure in, 90-97  
 Columbite, 45  
 Columbium, 24, 45, 72, 187, 188  
 Conglomerate, 19, 23, 30, 32, 35, 37-8, 41, 44, 53-4, 59, 76, 80, 87, 103, 106, 113, 116, 118-120, 128, 193-5, 197  
 Copper, 19, 27, 42, 53, 62, 77, 104, 112, 113, 115, 134, 154, 213, 215, 217, 219, 223, 231, 254-5  
     determination of, 221  
 Copper carbonate, 22, 129  
 Copper sulfate, 129  
 Copper sulfide, 28, 53, 129  
 Cordilleran Foreland, 34, 53, 83-89, 106  
     tectonic analysis, 87-88  
 Corvusite, 53  
 Counter, 135  
     coincidence, 168  
     equilibrium, 153  
     gamma-ray scintillation, 140  
     Geiger(-Müller), 101, 102, 139-144, 146-8, 150, 152, 154-5, 168, 174, 191, 268  
     circuit, 144  
     ionization, 102, 191, 268  
     scaler, 150  
 Counter (*Cont.*)  
     scintillation, 102, 139, 140, 142, 144, 148, 150-152, 156, 158, 168, 171, 173-4, 177, 191, 268  
 Crandallite, 44  
 Cryptanth, 229  
 Curie (unit), 232  
 Curite, 14, 16  
  
**Davidite**, 15, 16, 24-5, 57-8, 112  
 Desert blazingstar, 229  
 Detector, radioactivity, 135  
 Deuterium, isotopic abundance, 232, 234  
 Diatomaceous earth, 65  
 Diatomite, 42  
 Diatremes, 22  
 Dickite, 115  
 Discoveries, exploring, 107  
 Dolomite, 21-2, 29, 46, 119, 120  
 Dolomitization, 119, 120  
 Drill hole logging, *see* Logging  
 Drilling, 137, 138  
     cable tools, 258  
     calyx, 258  
     core, for outlining zones, 260-65  
     cost, 259  
     diamond, 153, 230, 257, 259  
     diamond core, 259  
     electrical, 203  
     exploration, 256-67  
     methods, evaluation, 258-60  
     percussion, 258-9  
     rotary, 257-9  
     spudding, 258  
     types of, 257-8  
  
**Epidote**, 125  
 Euxenite, 45, 73, 76, 121  
 Evaporites, 37  
 Exploration, underground, 137  
 Exploration drilling, 256-67  
 Exploration in France, 134-8  
  
**Feldspar**, 24, 31, 56, 74, 108-9, 112, 118, 124  
 Ferrugination, 116  
 Fir, 226  
 Fluorapatite, 31, 44, 68-9  
 Fluorine, 25, 29, 103, 111-12



Fluorite, 25, 29, 47, 52, 74, 112, 117-18, 121, 123  
 Fluoritization, 117

**Gabbro**, 215  
 Galena, 19, 57, 60, 117, 133  
 Gallium, 9, 41  
 Gamma radiation, detection, 141  
 Garnet, 44-5, 112, 125-6  
 Germanium, 41  
 Gneiss, 26-7, 30, 31, 57, 76, 111  
 Gold, 23, 30, 59, 60, 72, 153-4, 217, 235  
 Goldenweed, 229  
 Granite, 9, 26-30, 41, 46, 52, 56-7, 62-4, 67, 73-4, 76, 78, 80, 108-9, 121, 126, 131-3, 136, 170, 215  
 Granodiorites, 73  
 Graphite, 65, 66  
 Graywacke, 78  
 Great Bear Lake, 26  
 Grits, 44  
 Groundsel, threadleaf, 229  
 Gummite, 15  
 Gumweed, 228  
 Gunnar deposit, 26  
 Gypsum, 229, 265

**Hafnium**, 9  
 Helium, 39, 43, 113, 233, 269  
   isotopic abundance, 232, 234  
 Hematite, 52, 103, 116, 121, 124  
 Hornblende, 111, 112, 125  
 Hornblende schist, 111  
 Hornfels, 29, 76  
 Huminite, 43  
 Hydrocarbons, 19, 30, 62, 68  
 Hydrogen sulfide, 38, 58, 67, 110, 116

**Igneous rocks**, 52, 55-7, 108  
 Illite, 115, 117, 118  
 Ilmenite, 44-5, 57, 125  
 Instruments, calibration, 141-3  
   radiometric, circuits, 143-9  
   types, 139-41  
 Iron, 9, 17, 18, 21-2, 25, 41, 46, 57-8, 77, 102, 108, 111-13, 116-18, 231, 237, 265  
 Iron carbonate, 22, 113  
 Iron oxide, 17, 25, 27, 29, 57-8, 111-13, 129, 170

Iron silicate, 56  
 Iron sulfate, 113, 129  
 Iron sulfide, 27, 30, 53, 116, 129

**Jáchymov** (Joachimsthal), 28  
 Jarosite, 113  
 Jasper, 57  
 Joachimsthal, 28  
 Johannite, 15, 16  
 Juniper, 225-6

**Kaolin**, 115, 118  
 Kaolinite, 59, 115, 117-19  
 Kolm, 39, 66  
 Kolovratite, 77  
 Krypton-85, 232-3  
 Kyanite, 32, 125-6

**Lamprophyres**, 56  
 Laterite, 17  
 Lava, 20, 45  
 Lead, 2, 9, 10, 13, 16, 19, 27, 41, 55, 57-61, 112, 134, 213, 215, 217  
 Lead sulfide, 28, 53  
 Lee partitioning configuration, 194, 196, 203  
 Liebigite, 210  
 Lignite, 2, 18, 38-42, 52, 54, 63-65, 75, 79, 80, 87, 113, 248  
 Lily, 229  
 Limestone, 32, 37, 42, 53-4, 62, 68, 78, 85, 112, 193, 231  
 Limonite, 216  
 Lithium, 24  
 Lithology, influence of structure on, 85-7  
 Logging, borehole, 147  
   continuous velocity, 212  
   electric, 199, 200, 258, 259  
   in hole, 204, 205, 207-9, 212  
   resistance, 200, 201  
   gamma-ray, 114, 137-8, 145, 200, 258-9, 268-9, 272-3  
   in hole velocity, 200  
   neutron, 268-9  
   neutron-gamma, 269  
   neutron-neutron, 269  
   scintillation, 269-76

**Magnesium**, 9, 21-2, 47, 78, 108, 118, 120, 204-5, 237



- Magnesium carbonate, 46, 109  
 Magnesium silicate, 46, 56  
 Magnetite, 44, 45, 56, 123-5, 189  
 Magnetometry, air-borne, 181  
     field, 188  
 Manganese, 112, 113, 216  
 Manganese carbonate, 113  
 Manganese oxide, 111, 113  
 Marble, 111  
 Meta-autunite, 63, 248  
 Metamict minerals, 16  
 Metamorphic rocks, 108  
 Metatorbernite, 29  
 Metatyuyamunite, 63  
 Metazeunerite, 54, 248, 255  
 Meter, counting-rate, 140, 155  
     recording, 155  
     total-intensity, 140  
 Mica, 115  
 Migmatites, 24, 25, 46, 56-7  
 Millisite, 44  
 Minerals, heavy, and prospecting, 121-6  
 Molybdenum, 19, 41-2, 55, 104, 112, 113,  
     118, 217, 219, 254-5  
     determination of, 220  
 Molybdenum sulfide, 19  
 Monazite, 14, 15, 18, 23, 28, 31-2, 44-6,  
     73, 76, 112, 114, 121, 125-6  
 Montmorillonite, 115, 117-18  
 Montroseite, 53  
 Monzonite, 27, 29, 45  
 Mudstone, 34, 37, 53-4, 59, 103, 112-13,  
     128, 193-5, 200, 204, 207-8, 260-62,  
     264-6, 272-3  
 Mustard, tumble, 229
- Needle-and-thread**, 229  
 Nickel, 19, 27-8, 57-8, 112-13  
 Nickel sulfide, 27, 46  
 Niobium, 9, 56, 64, 104, 112, 215, 217, 219  
     determination of, 222  
 Niobium oxide, 9  
 Nitrogen, isotopic abundance, 232, 234
- Oil**, 19, 39, 42-3, 48, 61, 66-8, 89, 110, 114  
 Oil wells, 114  
 Olivine, 73  
 Onion, wild, 229  
 Orogeny, and uranium concentration, 77-9  
 Oxygen, isotopic abundance, 232, 234
- Paleochannels**, 126, 127  
     drilling patterns for, 265-7  
 Paleotopography, mapping techniques of,  
     129  
 Paramontroseite, 53  
 Peat, 40, 41, 64, 65, 75, 80  
 Pegmatites, 23, 24, 25, 31, 46, 56-57, 58,  
     71, 72, 73, 74, 75, 76, 77, 103, 106,  
     109, 114, 121, 192  
 Pepperweed, 229  
 Permeability, 205, 207-8  
 Petroleum, 19, 39, 40, 43, 60, 61, 68, 75,  
     80, 113, 114  
 Petroliferous material, 18, 38, 43, 47  
 Phosphates, phosphate rocks, 2, 3, 43-4,  
     48, 54, 66, 68, 108-9, 115, 134, 239,  
     268  
 Phosphorites, 43, 52, 54-5, 60, 66-9, 71,  
     77-8, 103, 114  
 Phosphorus, 18, 44, 53, 69, 112, 228, 254-5  
 Phyllites, 29  
 Pine, ponderosa, 226  
 Piñons, 225-6  
 Pitchblende, 10, 13-16, 19, 20, 24-8, 38,  
     46-8, 52, 56-8, 60, 74, 89, 106, 112,  
     115-18, 120-21, 129, 132, 134, 246  
 Placers, 114  
 Plagioclase, 56, 73, 118  
 Porosity, 205, 212  
 Porphyry, 170  
 Potassium, potash, 56, 73, 76, 109, 112,  
     142, 204-5, 210, 225, 237, 268-9  
 Potassium carbonate, 65  
 Potassium sulfate, 113  
 Primrose, 229  
 Prince's plume, 228  
 Probes, drill-hole, 102  
 Prospecting, aerial radiometric, 135  
     in Brazil, 177-91  
     Canada, 105-7, 191-2  
     U.S.A., 171-7  
     U.S.S.R., 164-71  
     air-drill, 105  
     air-ionization technique, 164  
     areo-gamma method, 166-9  
     borehole geophysical methods, 199-200  
     conifers in, 225  
     depth profiles in, 203  
     diamond drill, 105-6



Prospecting (*Cont.*)

- electric logging method, 105, 201-2, 207
- electrical methods, 194-7
- electrical resistivity methods, 105, 194-5, 199, 205, 208, 212
- electromagnetic induction method, 201-2
- engineering techniques, 105
- field techniques, 141
- gamma-ray logging, 105
- geobotanical, 104, 224-31
- geochemical, 104, 202, 213-23
- geologic, 102-3, 108-130
- geophysical, 104-5, 193-201
- geophysical-geochemical, 202-212
- ground methods, 106
- heavy minerals, 121-6
- high-frequency reflection method, 212
- hydrogeochemical, 232-55
  - in the U.S.S.R., 242-7; in U.S., 234-41
- induced polarization methods, 201
- in-hole resistivity method, 210
- magnetic methods, 201
- natural potential method, 197, 201
- use of non-core drill, 105
- province concept, 79-81
- radio wave attenuation, 200, 201
- radiometric, 105, 139-49
- reconnaissance data, 210-12
- resistivity method, 212
- rock alteration criteria, 115-21
- seismic, 105, 197-9, 212
- seismic reflection method, 201-2, 212
- seismic refraction method, 197, 201-2, 212
- self-potential in, 212
- surface electrical methods, 208
- surface-in-hole electrical methods, 200, 201
- surface radiometric method, 202
- surface resistivity method, 202-4, 206-7, 209-10
  - by tree analysis, 224-7
  - velocity logging method, 202
- Province concept, application to prospecting, 79-81
- Provinces, accumulation of thorium in, 9
  - accumulation of uranium in, 9
  - metalogenic, 9, 10, 214

- Pumice, 64
- Pyrites, 16, 17, 25, 27, 29, 39, 47, 57, 59, 66, 116, 117, 118, 121, 133, 231
- Pyrochlore, 9, 187, 188, 189
- Pyroxene, 73, 109
- Pyroxene Andesites, 119
- Quartz**, 25, 29, 30, 44, 57, 62, 74, 78, 108, 112, 116-17, 120, 122, 124, 132-3
- Quartz bostonite, 73-4
- Quartz monzonite, 45, 115, 117-18
- Quartz sandstone, 78
- Quartzite, 16, 29, 30, 44-6, 176
- Radiation detector**, 155, 171
- Radiometry, aerial, 155-92
  - interpretation of, 158-64
  - subsurface, 268-76
  - surface, 150-54
- Radium, 39, 43, 48, 113, 232-3, 242-4, 246
- Radium Hill, 24
- Radon, 39, 43, 104, 154, 164-6, 232-3, 242-4, 246, 268-9
- Rare earth oxides, 15
- Rare earth phosphates, 15
- Rare earths, 16, 18, 31, 41, 44-6, 56, 72, 112, 117, 187
- Rauvite, 53
- Recorder, 145, 148
- Rhyolites, 29
- Ricegrass, Indian, 228
- Roscoelite, 53
- Rutile, 57, 125
- Rye, Salina wild, 229
- Samarskite**, 76, 121
- Sandstone, 17, 18, 21-2, 32-4, 37-8, 40-42, 53-5, 59-64, 66, 71, 78-80, 85, 91, 103-4, 108, 111-13, 119-20, 127-9, 134, 193-5, 200, 201, 207, 215, 226-7, 230, 247-9, 257, 260-62, 264-6, 272-3
- Scapolite, 24
- Schist, 31, 57, 76-7
  - graphitic, 77
- Schroeckingerite, 15, 17, 20, 75, 103, 111
- Scintillation logging, 269-76
- Sediments continental shelf, 114
  - marine, 115
  - terrestrial, 115



- Selenides, 53  
 Selenium, 104, 112-13, 216-17, 219, 223, 225, 227-230, 254  
     determination, 221  
 Sericite, 29, 115  
 Shale, 2, 37-41, 48, 68-9, 78-80, 87, 110-11, 113, 118, 134, 156, 193-5, 248, 260  
     alum, 40, 67  
     bituminous, 38-40  
     black, 40, 52, 54-5, 66-9, 71-2, 76-8, 80, 103, 114, 242  
     carbonaceous, 18, 38, 40, 55, 60, 63-5, 77, 210  
 Shinarump channels, exploration of, 126-30  
 Shinkolobwe mine, 27  
 Siderite, 22, 116  
 Silica, silicates, silicon, 9, 16, 18, 22, 25, 53, 57-8, 65, 72-3, 75-6, 78, 112-13, 212  
 Silicification, 120  
 Sillimanite, 32, 125-6  
 Siltstone, 37-8, 85, 111, 113, 118, 194-5, 260  
 Silver, 2, 9, 28, 46, 57-8, 112-14  
 Sklodowskite, 15  
 Slate, 77  
 Sodium, 109, 204-5, 225, 237, 254-5  
 Southern Black Hills, 202  
 Sphalerite, 19, 116-17, 133  
 Sphene, 45, 56, 125  
 Spilite, 78  
 Spinel, 125  
 Stalactites, 20  
 Stauroilite, 32, 125-6  
 Structure, influence on lithology, 85-7  
     regional, influence on uranium occurrence, 83-98  
 Sulfur, sulfides, 25, 27, 38-9, 47, 52-3, 56-7, 59, 66, 104, 216-17, 225, 227-30, 235-6, 247, 265  
 Sulfur dioxide, 38  
 Surface radiometry, 150-54  
 Surveys, aeromagnetic, 158, 191  
     air-borne, 156-58  
     surface, 150-52, 154  
 Syenite, 73, 78, 103, 188-9  
  
**Tantalum**, 9, 24, 56, 72  
 Tantalum oxide, 9  
 Tennantite, 19  
 Tetrahedrite, 19  
 Thorianite, 15, 73, 121  
 Thorite, 15, 18, 23, 31, 43, 73, 114, 121  
 Thorium, 1, 7, 9, 10, 14-16, 18-20, 22-4, 31-2, 43-6, 48-9, 56-7, 61, 72, 101-4, 108-9, 112, 114, 117, 139, 142, 153, 158, 164, 168, 170, 177, 187, 202, 210, 213, 215, 217, 234, 268-9  
     ages of deposition, 10  
     deposition, 19-23, 31-2  
     deposits, types, 23-5  
     in detritus, 44-6  
     geology, 6 ff.  
     mineralogical features, 14  
     occurrence, natural, 7-51  
     prospecting techniques, 100 ff.  
     sources, original, 7-19, 46-9  
     transport, 19-23  
 Thorium oxide, 9, 18, 44, 117  
 Thorium phosphate, 18  
 Thorium silicate, 18  
 Thorogummite, 15, 18, 31  
 Thoron, 164-5  
 Thucholite, 15, 18, 19, 30, 38-9, 43, 60, 61, 116  
 Time scale, geological, 12  
 Tin, 9  
 Titanium, 45-6, 56-7, 64, 112  
 Topaz, 29  
 Torbernite, 15-18, 20, 54  
 Tourmaline, 125  
 Transistors, 143, 146-8  
 Tritium, 232  
 Trumpet, desert, 229  
 Tuff, 33, 39, 41-2, 54, 60, 61, 64, 80, 87, 91, 113, 119, 239, 248-9, 255  
     *see also* Volcanic ash  
 Tungsten, 9, 115  
 Turquoise, 77  
 Tyuyamunite, 15, 16, 20, 53  
  
**Ultramafic rocks**, 108  
 Umohoite, 118  
 Uraninite, 10, 13-18, 23, 25, 27-31, 43, 46, 52-4, 56-62, 73, 77, 121, 214, 215, 248  
     age of, 13



- Uranium, 1-3, 7, 9, 10, 13-20, 22-34, 36, 38-49, 52-69, 71-80, 83, 85, 87-92, 96-7, 101-6, 108-121, 126, 128-9, 131-4, 136-42, 151-4, 156-9, 164-6, 168, 170, 175, 177, 187, 192-3, 195, 197, 199, 200-202, 210, 212-17, 219, 222-57, 260-61, 268-9
- ages of deposition, 10
  - in bituminous strata, 38-43
  - by-product, 2
  - concentration of geological, 72-77
    - influence of orogeny, 77-79
  - deposition, 19-23
  - determination of, 219, 248
    - chromatographic, 227
    - fluorometric, 227, 234
  - distribution, stratigraphic, 33
  - districts, localization by tectonic elements, 88-9
  - exploration, in France, 131-38
  - genesis, 55-70
    - hydrothermal vein, 57-9
    - replacement, 57-9
    - in sandstone, 59-63
    - types, 23-5
  - geology, 6 ff.
  - in ground water, 248
  - mineralogical features, 14
  - occurrence, 7-51
    - influence of regional structure, 83-98
    - in the U.S.A., 52-4
  - in phosphate rock, 43-4
  - prospecting techniques, 100 ff.
  - provinces, 71-82
  - resources, 1-3
  - in sedimentary strata, 32-8
  - source beds, location by water sampling, 247-55
  - sources, 7-19, 46-9
  - transport, 19-23
  - in water, 238, 249-53
- Uranium carbonate, 17, 20, 27, 105
- Uranium molybdate, 27
- Uranium organic compounds and complexes, 14, 15, 18, 42, 63
- Uranium oxide, 9, 16, 17, 24, 27, 53, 117, 142, 150, 151, 159, 162, 268, 273
- cost, 2, 3
- Uranium phosphate, 18, 27, 132, 210, 248
- Uranium silicate, 15, 27, 59
- Uranium titanate, 57
- Uranium-vanadium minerals, 14, 17, 22, 34, 53, 77, 129, 260
- Uranocircite, 63
- Uranophane, 15, 19, 20, 27, 248-9
- Uranopilite, 15, 16
- Uranothorite, 45, 57
- Uranyl acetate, 69
- Uranyl alkali carbonates, 65
- Uranyl alkaline-earth carbonates, 65
- Uranyl arsenate, 75
- Uranyl carbonate, 58, 65, 75
- Uranyl compounds, 16, 39, 58, 66, 116
- Uranyl magnesium carbonate, 65
- Uranyl organic compounds, 39
- Uranyl phosphate, 75
- Uranyl potassium carbonate, 65
- Uranyl sodium carbonate, 65
- Uranyl sulfate, 16, 58, 65, 69, 75, 129
- Uranyl vanadate, 22, 75
- Vacuum tubes, see Valves**
- Vaesite, 27
- Valves, 143-6
- Vanadium, 17, 19, 41-2, 53, 59, 61-2, 104, 112-13, 129, 215-17, 219, 230, 254-5, 260
- determination, 220
- Vanadium oxide, 53
- Vetch, 228
- Volborthite, 77
- Volcanic ash, 19, 33, 48, 56, 60, 61, 78, 80, 96, 113, 248
- see also Tuff*
- Water**, electrical conductivity, 205
- uranium content, 238, 249-53
- Wavellite, 44
- Well logging, *see Logging*
- Wenner configuration, 203
- Wind River Basin, 208
- Witwatersrand, 30
- Wood, 59, 61, 65, 116
- carbonized, 113
  - coalified, 17, 18, 53
  - fossil, 18
  - silicified, 128, 193
- Xenon-133**, 232-3
- Xenotime, 14, 15, 18, 23, 56, 73, 76, 125



Yttrium, 19  
Yttrocrasite, 15

Zeunerite, 15

Zinc, 2, 9, 27, 104, 112-13, 115, 213, 215-  
17, 254-5

Zinc sulfide, 28, 53

Zippeite, 15, 16

Zircon, 23, 45, 56, 73, 76, 114, 125-6

Zirconium, 31, 187

Zirkelite, 15

Zones, outlining by core drilling, 260-65



## NAME INDEX

---

- ADAMS, J. A. S., 57  
 Ahrens, L. H., 214  
 Amiel, S., 232  
 Anderson, R. Y., 227
- BACHMAN, 63  
 Bain, G. W., 44, 74  
 Bannister, F. A., 16, 24  
 Baranov, V. I., 164  
 Barth, T. F. W., 24  
 Barthelmes, A. J., 197  
 Bate, G. L., 28  
 Baumgardner, 157  
 Beath, O. A., 228  
 Bennett, J. A. E., 24  
 Bisby, H., 143  
 Black, R. A., 193  
 Bodine, M. W., Jr., 22  
 Bowie, S. H. U., 30, 73, 101, 121, 154, 213  
 Boyle, T. L., 171  
 Bray, 117  
 Breger, I. A., 18, 65  
 Brophy, G. P., 20  
 Brown, 117  
 Burbank, 89  
 Buttenbach, H., 15
- CANNEY, F. C., 213  
 Cannon, H. L., 224  
 Carmichael, 160  
 Casey, R. D., 197  
 Chester, J. W., 256  
 Cohen, W. J., 16  
 Collins, C. B., 13  
 Comstock, S. S., 269  
 Cook, J. W., 160  
 Craig, L. C., 260
- DAHL, H. M., 20, 117  
 Dana, 16
- Davidson, C. F., 9, 23, 24, 30, 60, 101, 121, 154, 213  
 Dawson, K. R., 116  
 Denson, M. E., Jr., 202  
 Denson, N. M., 60, 63, 64, 247  
 Derzay, R. C., 28  
 Deul, M., 18, 65  
 Di Giovanni, H. J., 269  
 Dodd, P. H., 260
- ELLSWORTH, H. V., 16, 19  
 Elmore, W. C., 168  
 Erickson, R. L., 61  
 Everhart, D. L., 25, 28, 55
- FANO, 159  
 Farquhar, R. M., 13  
 Faul, H., 10  
 Fisher, N. H., 17  
 Fix, P. R., 234  
 Fleischer, M., 9  
 Franke, K. W., 221  
 Franklin, E., 143, 160  
 Fraser, J. A., 26, 27  
 Fredrickson, 66  
 Froelich, H. F., 224  
 Frondel, C., 18
- GARDINER, 119  
 Garrels, R. M., 28, 55  
 Geiger, 140  
 Giletti, B. J., 28  
 Glebov, 67  
 Goldschmidt, V. M., 61, 67  
 Gott, 61, 65  
 Graveson, R. T., 269  
 Green, J., 20  
 Grimaldi, F. S., 227  
 Grundy, W. D., 126, 265



Gruner, J. W., 16, 119  
Guedes, S. V., 177

HAYCOCK, M. H., 16  
Hewitt, D. F., 24  
Hillebrand, W. F., 221  
Horne, J. E. T., 16, 24  
Hunt, E. C., 220, 223  
Hurley, P. M., 73

JOHNSON, J. C., 1  
Joubin, F. R., 30

KELLER, G. V., 199  
Kelley, D. R., 22  
Kelley, V. C., 90  
Kerr, P. F., 7, 20, 22, 115, 117  
Keys, W. S., 22  
Kidd, D. F., 16  
King, J. W., 42  
Kleinhampl, F. J., 224  
Klepper, M. R., 10, 71  
Korff, S. A., 168  
Kulp, J. L., 28, 118  
Kurtz, E. B., Jr., 227

LAKIN, H. W., 213  
Lang, A. H., 24, 75, 105, 152, 191  
Larsen, E. S., Jr., 9, 56, 73  
Lenoble, A., 131  
Louw, J. D., 60  
Lovering, T. S., 22, 117, 213  
Lowell, J. D., 34

MACFADYEN, D. A., 177  
McKelvey, V. E., 28, 55  
Mackin, J. H., 22  
Manger, G. E., 200  
Milkey, R. G., 59, 60  
Miller, L. J., 38  
Miller, R. E., 199  
Moore, G. W., 65, 69  
Moxham, R. M., 157  
Müller, 140

NARTEN, P. F., 224  
Neuman, 69  
Nier, A. O., 13, 14  
Nininger, R. D., 101  
North, A. A., 220

OSTERWALD, F. W., 83  
Overstreet, W. C., 121

PAGE, L. R., 17, 53, 56, 64, 108  
Peirson, 160  
Phair, G., 9, 56, 73, 117  
Pitman, R. K., 260

RANKAMA, K., 9  
Rasor, C. A., 17  
Robinson, S. C., 14, 15, 16, 27  
Rubinstein, S., 65  
Russell, R. D., 13

SAHAMA, T. G., 9  
Sakakura, A. Y., 158  
Sands, M., 168  
Satterly, J., 24  
Saukoff, A. A., 242  
Schmidt, D. L., 22  
Senftle, F. E., 153  
Sheridan, D. M., 111  
Shimamoto, K. O., 117  
Shoemaker, E. M., 22  
Smith, 68  
Spencer, 159  
Stead, F. W., 139, 150, 155, 268  
Stephens, J. G., 247  
Stern, T. W., 10, 59, 60  
Stieff, L. R., 10, 59, 60  
Stone, J., 121  
Strøm, 67  
Sullivan, C. J., 17  
Szalay, S., 65

TAYLOR, D., 143  
Theobald, P. K., Jr., 121  
Thurlow, E. R., 29  
Tom, C. W., 260  
Turner, 64

UREY, H. C., 9

VOGEL, C. B., 212

WALKER, 157  
Wantland, D., 197  
Ward, F. N., 213  
Weeks, A. D., 118, 119



Wells, R. A., 220  
Whitlow, J. W., 121  
Whitmore, F. C., 68  
Winsberg, L., 232  
Wood, H. B., 126, 265  
Woolard, L. E., 20

Wright, R. J., 25, 28  
Wyant, D. G., 10, 17, 20, 71  
  
YOLI, A. H., 269  
  
ZELLER, H. D., 63, 247





